FINAL REPORT FOR CONTRACT M67004-99-0034

SBIR TOPIC N99-037

REAL-TIME OBSTACLE DETECTION
USING A STREAK TUBE IMAGING LIDAR (STIL) (U)

Reporting Period: 5/21/99 to 11/20/99

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6. AUTHORS
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Arete Associates, 5000 Van Nuys Blvd., P.O. Box 6024, Sherman Oaks, CA 91430	8. PERFORMING ORGANIZATION REPORT NUMBER ART-99-507-007-TR

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13. ABSTRACT (Maximum 200 words)
Report developed under SBIR contract.

Grazing incidence LIDAR has been demonstrated for detection of shallow objects at significant standoff ranges. Practical application of this technique for collision avoidance from small maneuverable watercraft requires development and integration of a compact, rugged configuration that can provide high resolution imaging over a wide swath from a maneuvering platform, with sufficient standoff range to allow the operator to avoid the detected obstacle.

Areté Associates has developed a novel 3-D Imaging LIDAR system, the Streak Tube Imaging LIDAR (STIL), which can provide high resolution imaging at significant standoff ranges. The patented STIL approach is based on application of mature technologies, and has been demonstrated in the laboratory, ship-based experiments, and airborne demonstrations. STIL uses fan beam illumination, push broom imaging, and electrostatic sweep to generate high resolution images with no moving parts, yielding a rugged compact configuration for vehicle integration.

Areté Associates directly demonstrated STIL for obstacle detection at near grazing incidence by adapting and utilizing existing, proven hardware for a cost-effective experimental validation of the concept in Phase I. Prototype system development will follow in Phase II, and include detailed design, fabrication, integration, and demonstration of a compact, fieldable prototype configuration for vehicle mounted obstacle detection.

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  - Summary

SECTION I

INTRODUCTION

While operating at high speed, watercraft are extremely susceptible to collision with floating and submerged objects. Mission requirements for high speed amphibious operations demand a capability for detection of such hazards to navigation at sufficient stand-off range to avoid collision with the obstacle. Traditional acoustic techniques have significant limitations for detection of floating and shallow objects, and passive optical techniques have limited capability for detection of submerged objects at significant standoff ranges (as well as having no capability at night).

Active optical techniques overcome these limitations. LIDARs operating at blue-green wavelengths with short laser pulsewidths and time resolved receivers are capable of detecting submerged objects in the ocean, and have been effectively utilized in mine countermeasures applications from both aircraft and submerged vehicles. For the surface ship obstacle avoidance mission, LIDAR detection of submerged obstacles at significant standoff ranges was demonstrated over twenty years ago. [1,2] However, the demonstrations were at grazing angles of about 5°, and the technology available at the time was not mature enough to support a rugged, compact configuration suitable for the collision avoidance mission. For the Advanced Amphibious Assault Vehicle (AAAV), the required stand-off ranges and available mounting height above water require grazing angles of about 1° to 2°. In the Phase I effort under this contract, Arete Associates investigated the

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[1] Richard D. Anderson, R. F. Howarth, and G. C. Mooradian, "Grazing Angle LIDAR for Detection of Shallow Submerged Objects", Proc. Int. Conf. Lasers, pp 68-77 (1978)

[2] Richard D. Anderson, R. F. Howarth, and G. C. Mooradian, Detection of Shallow Submerged Obstactles by Two-Color LIDAR at Angles of Incidence Approaching 90 Degrees", SPIE vol 160 Ocean Optics V, pp 166-173, (1978).

feasibility of a LIDAR providing detection of floating and submerged obstacles at sufficient stand-off ranges over sufficient swath widths in a compact configuration suitable for deployment on the AAAV.

Areté Associates' patented **S**treak **T**ube **I**maging **L**idar[3] (STIL) is an innovative imaging LIDAR system based on a unique application of mature technologies. This technology has been developed for electro-optic identification of mines and other obstacles, and has demonstrated high resolution underwater imaging at significant stand-off ranges. In Phase I Areté Associates adapted this proven technology to a grazing incidence LIDAR configuration to investigate the feasibility of STIL to provide a robust solution for the Marine Corps obstacle avoidance requirement.

Grazing Incidence LIDAR for Marine Collision Avoidance: Overview

The basic concept behind grazing incidence LIDAR detection is illustrated in Figure 1. A narrow blue-green laser beam is projected from the ship at near grazing angle to intersect the ocean surface at large standoff range. Refraction at the water surface bends the beam into the water volume. Backscattered light from floating and submerged objects in the beam, as well as returns from the bottom are collected by a range resolved receiver co-located with the laser transmitter. Objects are detected by the excess photon return from the targets, or by their shadows. Detection of submerged objects by this technique was demonstrated over twenty years ago, and variants of that technique continue to be investigated for mine countermeasures applications.[4]
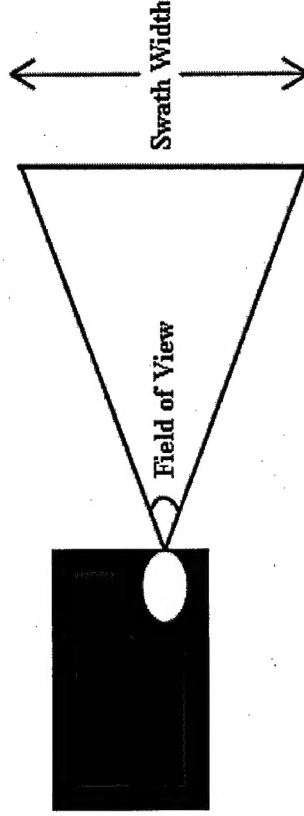
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[3] Patent Number 5,467,122, issued 14 November 1995.
[4] James G. Leatham, B. A. Speer, C. H. Waldman, K. E. Davies, and B. A. Swartz, "Grazing Angle Imaging LIDAR for Organic Ship MCM", Proc. Third Int. Symp. On Tech. and the Mine Problem, 6 April 1998, NPS, Monterey, CA
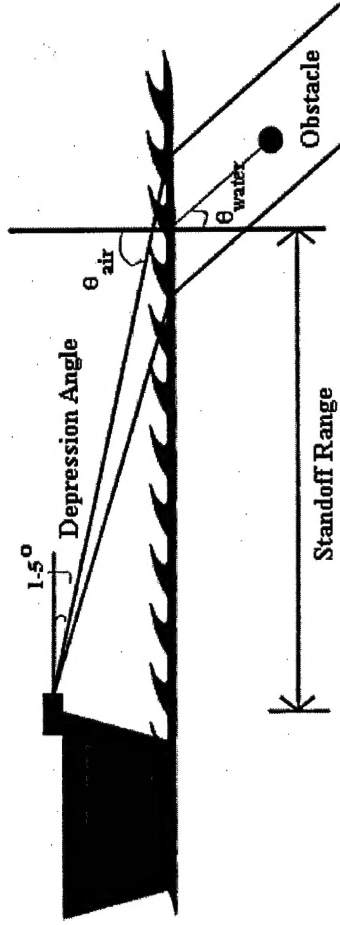
$$in-track\ sampling = \frac{forward\ speed}{pulse\ repetition\ frequency}$$

$$standoff\ range = \frac{sensor\ height}{\tan(depression\ angle)}$$

$$crosstrack\ sampling = \frac{swath\ width}{\#\ of\ receiver\ pixels}$$

$$swath\ width = 2 * standoff\ range * \tan\left(\frac{FOV}{2}\right)$$

Figure 1: Grazing Incidence LIDAR Viewing Geometry

The Marine's collision avoidance application requires detection of floating and submerged objects from a small, fast, and maneuverable craft such as the Advanced Amphibious Assault Vehicle (AAAV). Sensor requirements for this application include a wide swath width and large stand-off range to allow sufficient maneuvering volume to avoid the obstacle, sufficient spatial resolution and signal-to-noise ratio (SNR) to allow reliable detection of objects in a cluttered environment, and a physical configuration that is small and rugged to withstand the rigors of deployment on a combat vehicle. Areté Associates has developed and demonstrated a novel LIDAR implementation called the Streak Tube Imaging LIDAR (STIL) that provide high resolution 3-D imaging in a compact configuration (Figure 2).

The STIL approach is to project a very thin fan beam ahead of the vehicle to achieve a wide swath, and to image the illuminated strip onto the slit photocathode of a streak tube (Figure 3). Photons liberated from the photocathode are accelerated and deflected using a time varying electrostatic sweep. This sweep provides temporal (range) resolution of the backscattered returns. The resulting 2-D (range-azimuth) image is read out from the streak tube using conventional CCD electronics. The in-track dimension is sampled by repetitively pulsing the laser as the vehicle moves forward. In Phase II the data will be processed in real time to provide the operator with a view of the scene in front of the vehicle with obstacles highlighted (Figure 4).
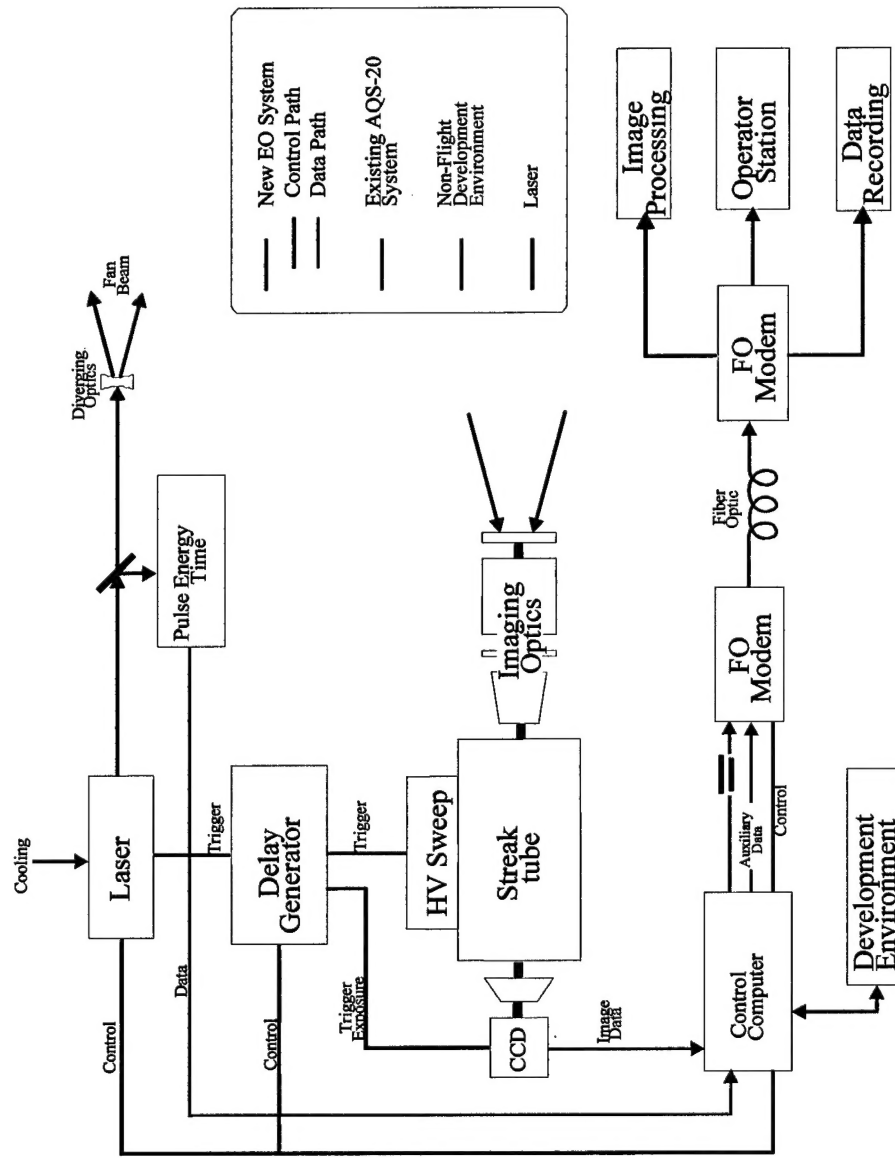
Figure 2. Streak Tube Imaging LIDAR block diagram. The EO sensor head occupies < 2 cubic feet. Data to the operator is linked using a fiber optic cable.
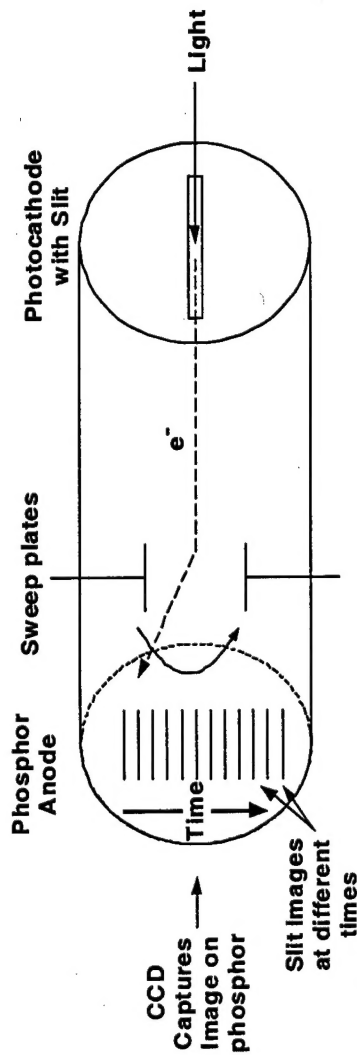
Figure 3. Streak Tube imaging, illustrating slit illumination and electrostatic sweep.

STIL technology has been developed by Areté for mine countermeasures applications, including high resolution 3-D imaging from underwater vehicles for mine identification[5], and high speed airborne surveillance for minefield detection.[6] In addition, Areté is pursuing commercial applications of STIL ocean surveillance technology, such as commercial fish finding and bathymetry.

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[5] "Mine Identification Using a Streak Tube Imaging LIDAR", ONR contract number N00014-98-C-0006.

[6] "Streak Tube Imaging LIDAR for High Speed Littoral Surveillance", FY98 Advanced technology Demonstration conceptual design, 12 March 1996.
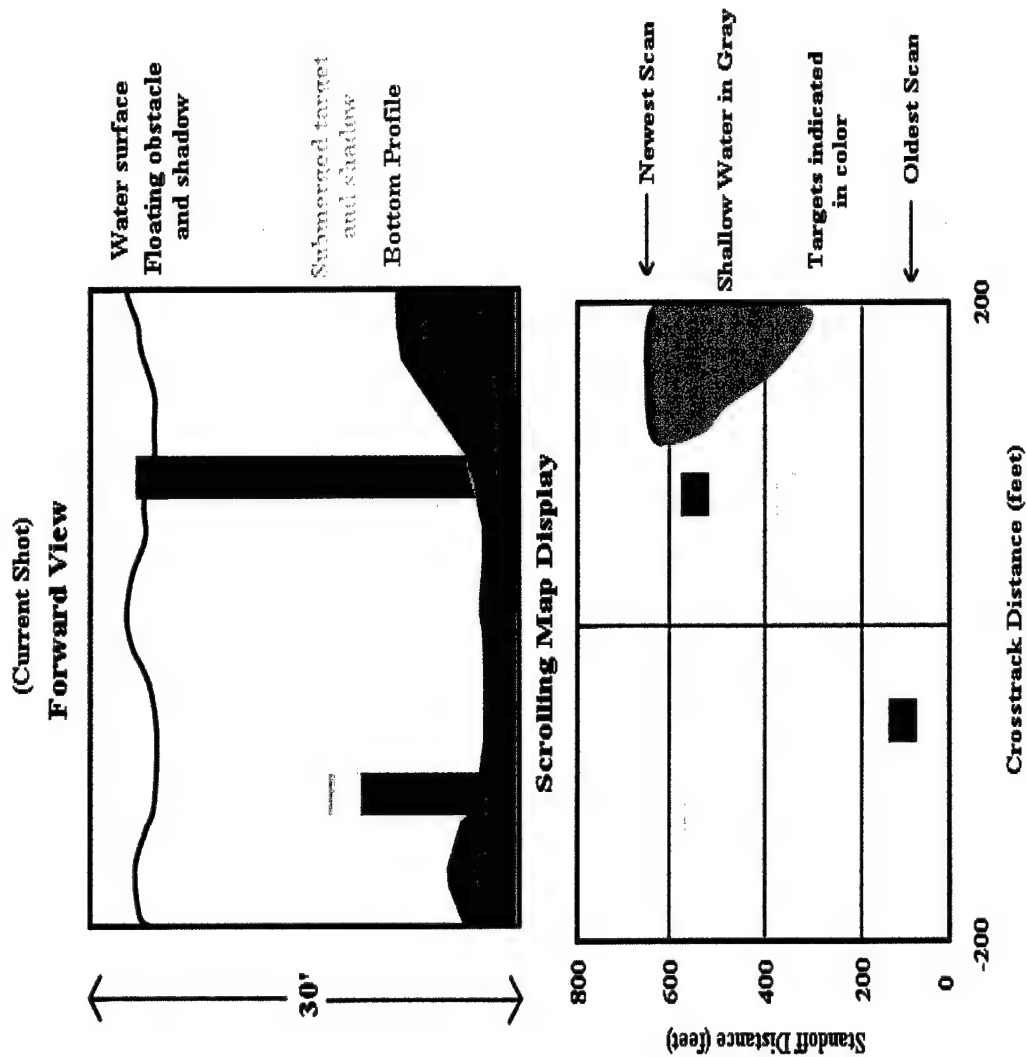
(Current Shot)
Forward View

Water surface
Floating obstacle
and shadow

Submerged target
and shadow

Bottom Profile

30'

Scrolling Map Display

Newest Scan

Shallow Water in Gray

Targets indicated
in color

Oldest Scan

200

Crosstrack Distance (feet)

-200

800

600

400

200

0

Standoff Distance (feet)

Figure 4: Grazing Incidence LIDAR Display Concepts

Summary

In Phase I, both modeling and field testing of the STIL prototype were accomplished. Existing STIL equipment was modified to operate at grazing incidence by adding a computer controlled single-axis elevation scan mirror. The field testing was performed at a local water park from a static ground position. The large wave pool at the water park provided significant standoff distances (~ 200 ft.), significant swath width (~44ft.), and controlled wave heights from flat (no waves) to 2 feet wave height. Three field test deployments were made to collect data at grazing angles from 0.5° to 2.7°, and under flat and wavy surface conditions. The STIL sensor was placed on a scissor lift which varied the sensor height to vary the grazing incidence angle.

The field test data was analyzed and compared to the model predictions. Laboratory radiometry measurements were made on the STIL prototype for input to the analytical models for comparison of model predictions to the field test data. The field test data agreed with the model predictions (see Section II for details).

A summary of the test results is as follows (see section II for details):

Detection of Floating Obstacles:

– Detected in All Cases even at 994 times Lower Power-Aperture Product than Submerged Obstacles

– Floating Obstacles are Much Brighter Than Submerged Obstacles, Bottom, and Water Surface

– As Expected, Waves Degrade Floating Obstacle Signal by Lowering the Mean Signal and Increasing Signal Fluctuations

Detection of Submerged Targets:

- Detected at Grazing Angles greater than 1.7° at full power-aperture product

- Not Detected at Grazing Angles lower than 1.5° at full power-aperture product

- Not Detected at low power-aperture product at any tested grazing angle

- Waves Improve Detectability if Observed over at least a Wave Period by Increasing the Mean Signal even though they also Increase Signal Fluctuations

The analytical models were also exercised to identify the performance envelope of the STIL concept in detecting floating and submerged obstacles at different incidence angles, and under degraded atmospheric conditions (haze and fog) and turbid water conditions (ocean to coastal water types). The experimental and model results were used in trade studies to develop an initial top-level design for a compact Phase II prototype STIL for obstacle detection. In order to reduce risk and cost, the Phase II prototype conceptual design leverages existing STIL hardware and software developed by Arete Associates under a contract with ONR for an underwater STIL for the Electro-Optic IDentifification (EOID) of mines. The Phase II prototype conceptual design also addresses operation in sea state 3 conditions by providing observation of the target over at least one wave period to mitigate against wave shadowing of the target. The Phase II prototype will be a bolt on prototype for ease of installation and removal from the AAAV test vehicle. The existing STIL breadboard prototype allows collection of real sea data early in Phase II to feed into the final Phase II hardware and software design.

Conclusions

Analytical models of the performance of the Streak Tube Imaging Lidar (STIL) for floating and submerged obstacle detection at grazing incidence were developed and confirmed with laboratory and field test data. The existing STIL breadboard prototype was modified for operation at grazing incidence. Three field test deployments of the STIL breadboard prototype were made to collect data on floating and submerged obstacles at grazing incidence angles under calm and wavy conditions. In the field tests, both floating and submerged obstacles were detected at grazing incidence angles using the STIL prototype. Detection of submerged obstacles required a much larger power aperture product than did the detection of floating obstacles.

The modeling and test data indicated that a compact STIL prototype leveraging current hardware and software would have excellent performance even in sea state 3 with moderate fog for the detection of floating obstacles in both the high speed and transition modes. Detection of submerged obstacles in transition mode may be feasible with a compact STIL system, but the reliability of the detection is problematic since the beam divergence in elevation necessary to provide observation over an entire wave period. Unfortunately, a much larger power aperture product lidar system would be required to detect submerged obstacles at the requisite grazing incidence angles, stand-off ranges, and swath widths in high speed mode. Since the AAAV hydroplanes in high speed mode so that the vehicle's draught is only one to two feet, submerged obstacle detection is of lesser concern than floating obstacle detection in high speed mode. The STIL system can provide excellent performance for the detection of floating obstacles, which are the most difficult obstacles for a sonar to detect because of surface wave noise. The STIL system for floating obstacle detection has the potential to move to operation at an eye safe wavelength in Phase III.

SECTION II
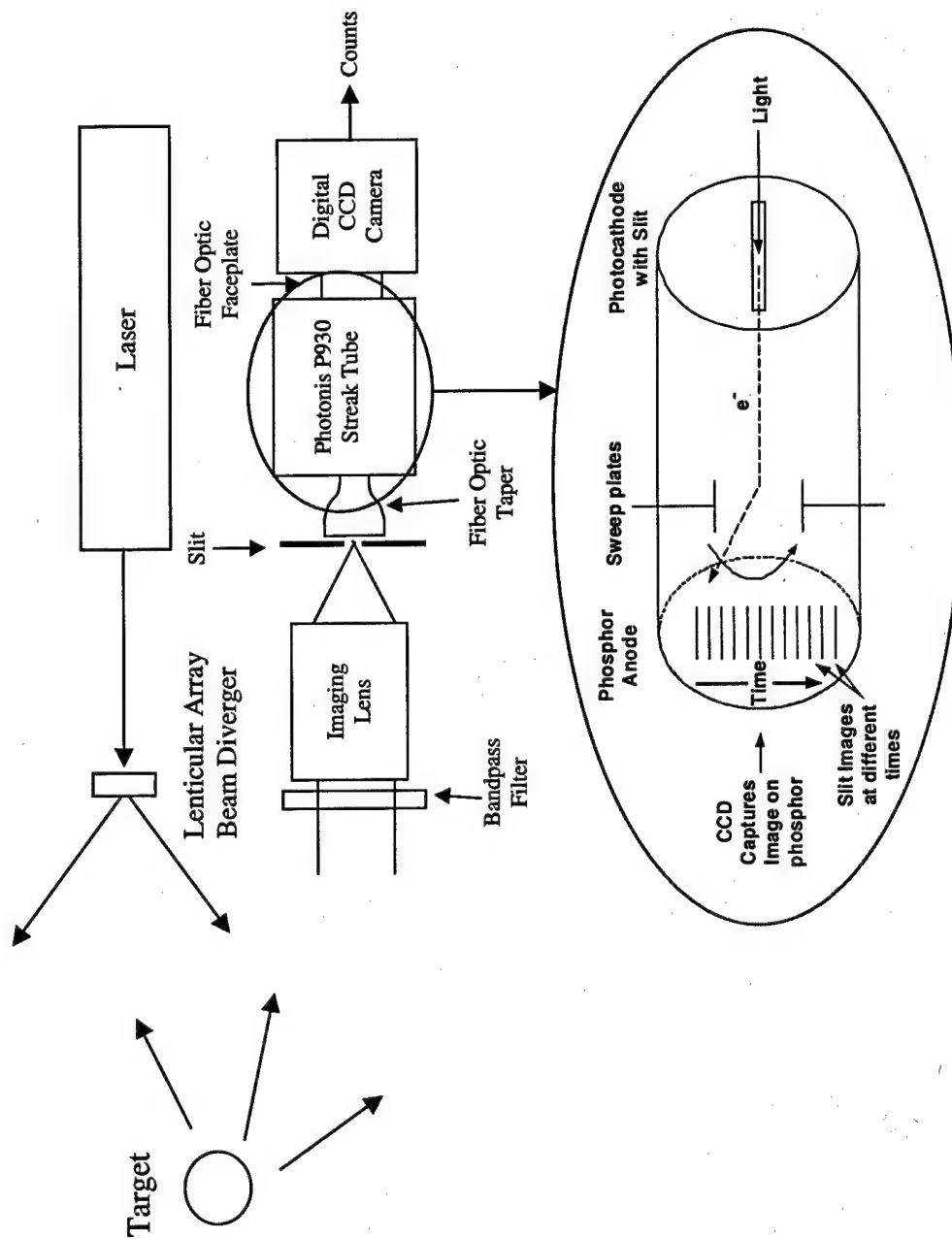
PROJECT OVERVIEW

- **Purpose:** Demonstrate detection of floating and submerged objects at significant standoff ranges and grazing incidence angles using an existing LIDAR breadboard prototype.

- **Approach:**

  - Adapt the existing Airborne Streak Tube Imaging LIDAR (ASTIL) prototype for grazing incidence angle operation

  - Collect data at a local water park for calm and wavy conditions.

  - Process STIL images to detect floating and submerged targets.

  - Develop conceptual design for a Phase II prototype (Option)

- **Funding:** $70 K (+ $ 30 K Option)

- **Period of Performance:** 6 months (+ 4 month Option)

- **Personnel:** Brian Redman (Principal Investigator), Lisa Bryan, Glen Redford, and Bill Ryder

STREAK TUBE IMAGING LIDAR (STIL) CONCEPT OF OPERATION

Target

Laser

Lenticular Array Beam Diverger

Fiber Optic Faceplate

Slit

Imaging Lens

Photonis P930 Streak Tube

Digital CCD Camera

Counts

Fiber Optic Taper

Bandpass Filter

Photocathode with Slit

Light

Sweep plates

e⁻

Phosphor Anode

Time

CCD Captures Image on phosphor

Slit Images at different times

STIL ADVANTAGES

- **Scannerless** operation for moving platforms

- **Commercial off-the-shelf (COTS) receiver components** such as **conventional CCD arrays and streak tubes**

- **COTS transmitter components** such as **moderate power lasers**

- **Ultra-high speed temporal sampling** without complex transient digitizers

- **Immune to solar background noise** for robust **day/night** operation

- **Scaleable** to a variety of along track, cross track, and range resolutions required for various of applications.

- **Ease of installation:** Mast mounting - No hull modifications

GRAZING INCIDENCE LIDAR VIEWING GEOMETRY

1.5°

Depression Angle

θ_{air}

θ_{water}

Obstacle
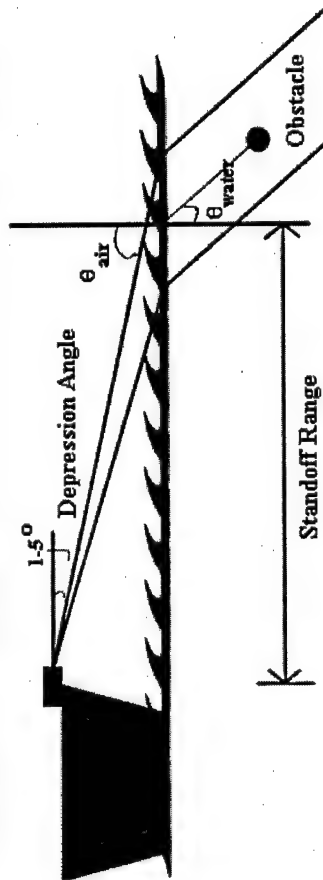
Standoff Range

$$standoff\ range = \frac{sensor\ height}{\tan(depression\ angle)}$$

$$in-track\ sampling = \frac{forward\ speed}{pulse\ repetition\ frequency}$$

Swath Width

Field of View
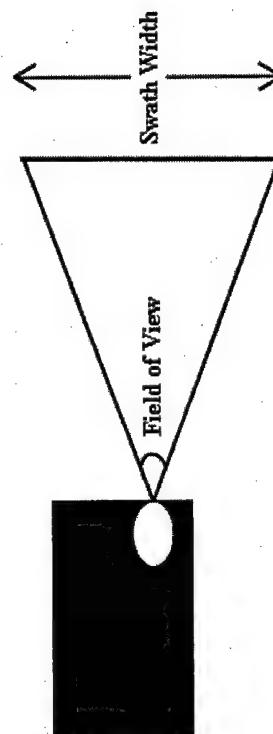
$$swath\ width = 2 * standoff\ range * \tan\left(\frac{FOV}{2}\right)$$

$$crosstrack\ sampling = \frac{swath\ width}{\#\ of\ receiver\ pixels}$$

PHASE I

PHASE I

TECHNICAL OBJECTIVES

- **Modify existing Prototype for Grazing Incidence Operation**
  - Add scanner, scanner controller, inclinometer, and mobile platform
  - Characterize Sensor and Targets in the Lab

- **Collect Water Data**
  - At Representative Stand-off Ranges and Incidence Angles
  - With and without waves

- **Model Lidar Return Signal**
  - Analytical Model for no waves
  - Analyze Wave Data for Detection Statistics

- **Top-level Trade Studies to assess performance in turbid water and fog**

- **Assess Eye Safety**

- **Conceptual Design for Phase II prototype**
  - Option: 4 month, $ 30 K

PHASE I
ACCOMPLISHMENTS

- **Modified ASTIL Prototype for Grazing Incidence Operation**
  - Added scanner (simulates forward motion of AAAV)
  - Added mobile platform for transport to pool tests

- **Characterized Sensor and Targets in Laboratory**
  - Measured Target Reflectances; Transmitter and Receiver Calibration

- **Collected Data: 3 Data Collection Deployments at Breakers**

- **Created analytic model of Lidar return signal for No Waves case**
  - Good match with data

- **Analyzed Data with Waves for Detection Statistics**

- **Estimated performance in turbid water and fog**

- **Assessed Eye Safety**

PHASE I TASKS AND SCHEDULE

Task	1 MAC	2 MAC	3 MAC	4 MAC	5 MAC	6 MAC	7 MAC	8 MAC	9 MAC	10 MAC
1. System Adaptation										
2. Grazing Angle Radiometry										
3. Full Scale Demonstration										
4. Final Report										
5. Conceptual Design (option)										

PHASE I DATA COLLECTION AT BREAKERS WATER PARK

VIEWS OF TEST SITE AT BREAKERS WATER PARK
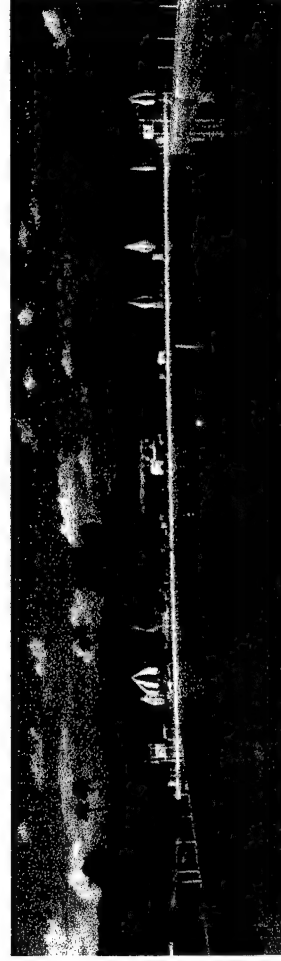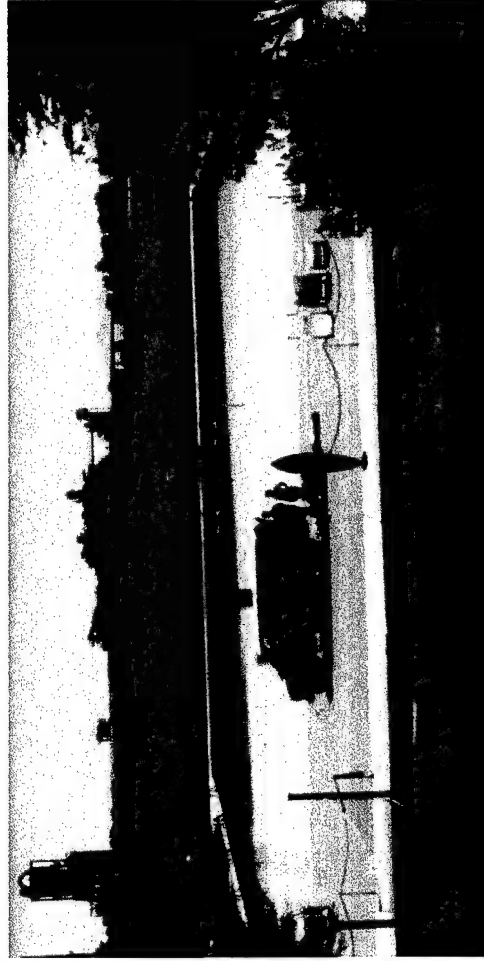
ASTIL PROTOTYPE ON SCISSOR LIFT AT BREAKERS WATER PARK
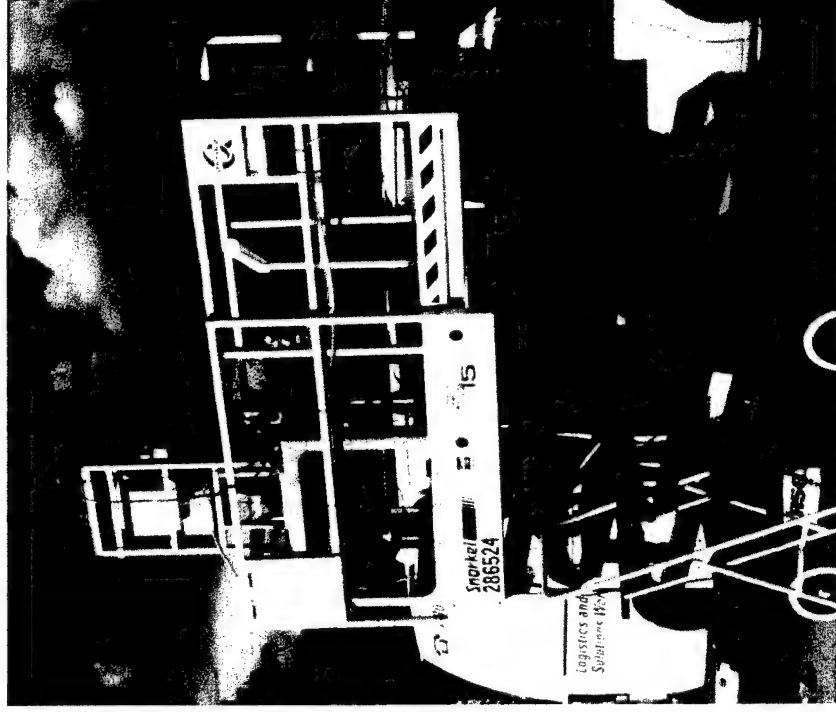
TESTS AT BREAKERS WATER PARK

- **Test Site:**

  – Provided significant standoff distances (~ 200 ft.)

  – Provided significant swath width (~ 44 ft.)

  – Provided controlled wave heights (~ 1 ft. to 2 ft.)

- **Grazing incidence angles for which data were collected:**

  – Deployment 1: Grazing Angles ~ 0.5° - 1.5° no waves and with some waves

  – Deployment 2: Grazing Angles ~ 1.7° - 2.7° no waves and with some waves

  – Deployment 3: Grazing Angles ~ 1.5° - 2.6° waves and some no waves

DATA EXAMPLES
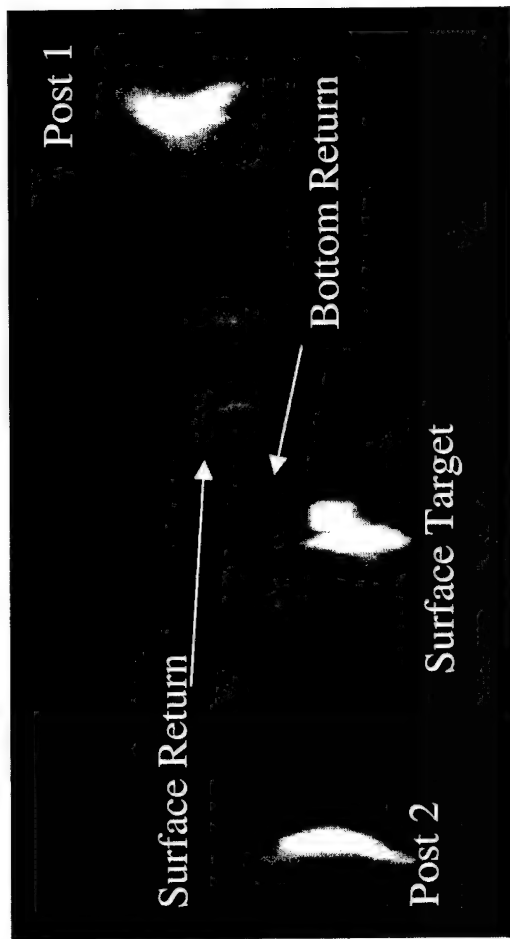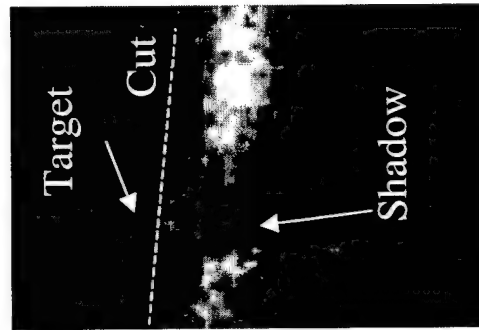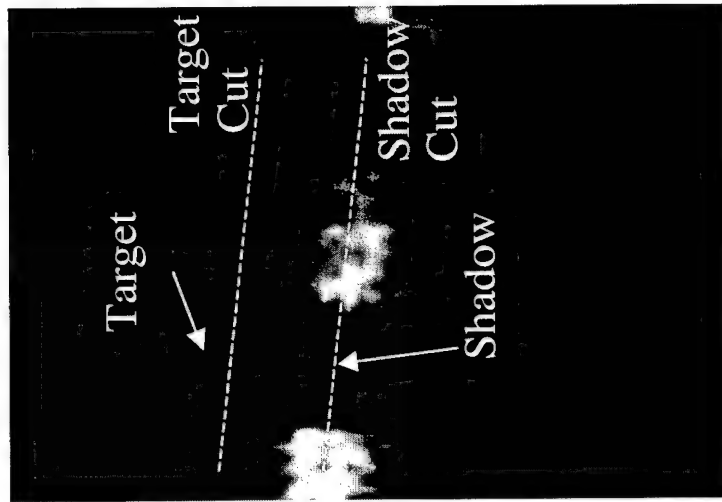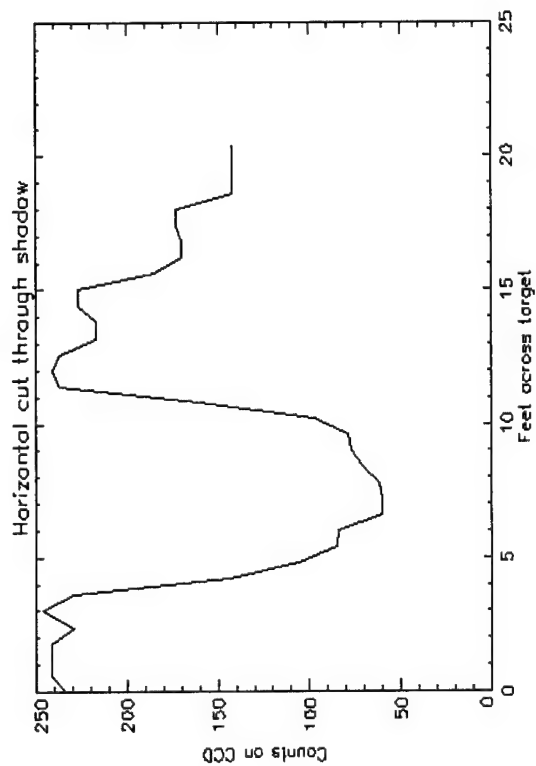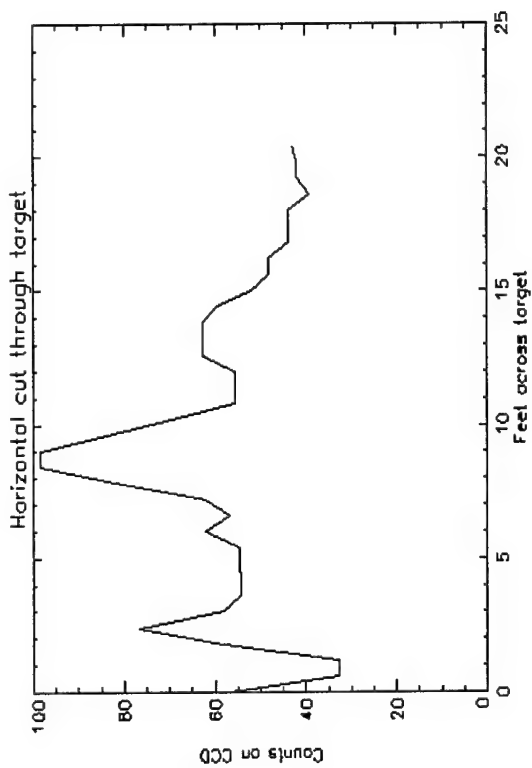
Surface and bottom returns
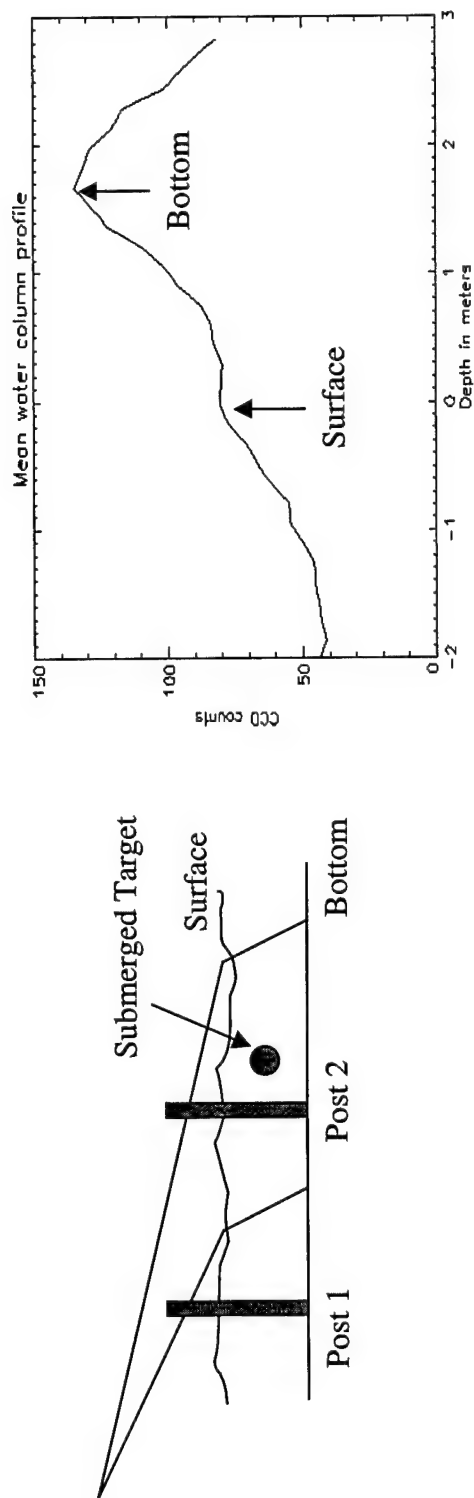
Range-Azimuth Intensity Images
2 ft. Submerged White Sphere At Different Grazing Angles

Target

Cut

Shadow

8.5' (2.6°)

2ft White Sphere, Sensor Height 8.5 feet

7.5' (2.3°)

2ft White Sphere, Sensor Height 6.5 feet

6.5' (2°)

2ft White Sphere, Sensor Height 7.5 feet

5.5' (1.7°)

2ft White Sphere, Sensor Height 5.5 feet
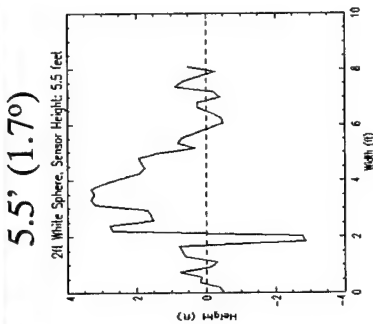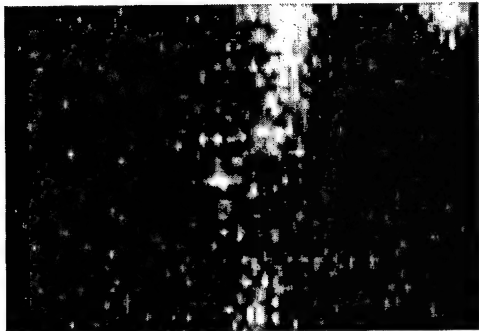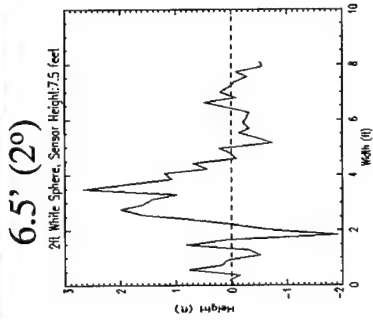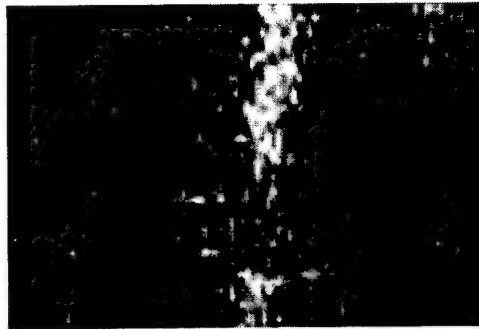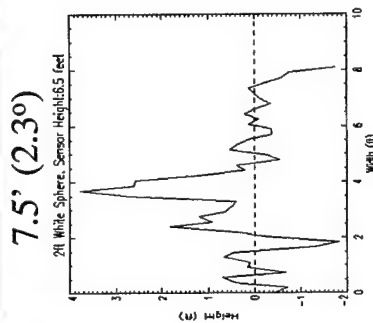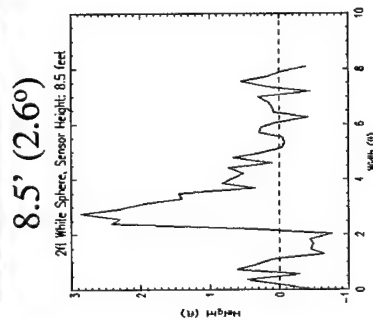
- **SNR Decreases as Grazing Angle Decreases**

- **Dark Targets Detectable by Shadow**
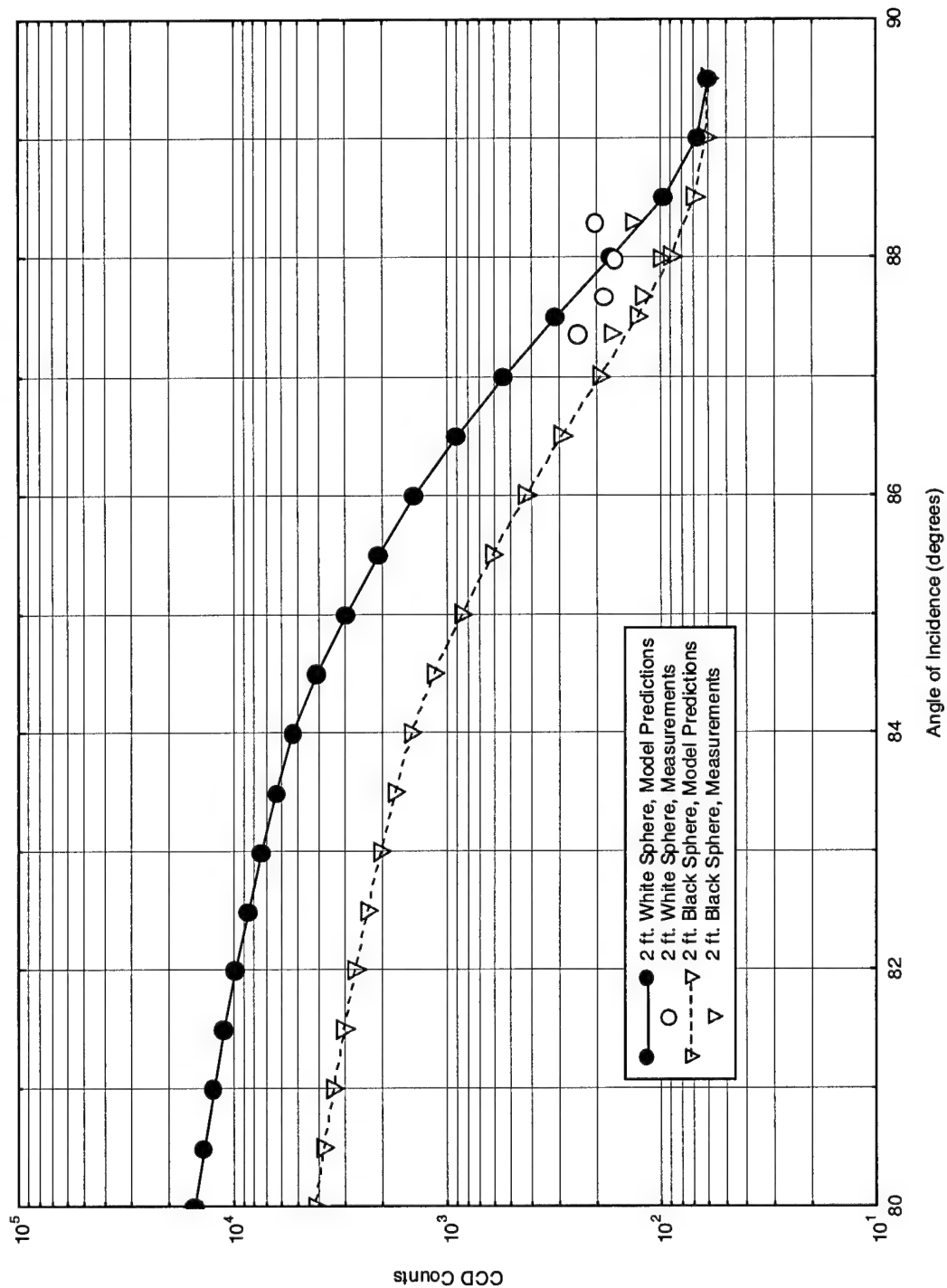
MODEL FOR GRAZING LIDAR SIGNAL
(No Waves)

EFFECTS OF GRAZING INCIDENCE
ON LIDAR RETURNS FROM SUBMERGED TARGETS

- **Fresnel Transmission Roll-off at Grazing Incidence**

- **Receiver Solid Angle Compression for Submerged Targets**

- **Signal Loss due to Elongation of the Laser Spot Along Track**

- **Maximum Achievable Grazing Incidence Angle is Limited**

    - Maximum Allowable Height Above Water for the Sensor

        - ~ 8.8' High Speed Mode
        - ~ 3.8' Transition Mode

    - Minimum Required Stand-off Range:

        - ~300' High Speed (~ 7 second warning at 25 knots)
        - ~ 85' Transition Mode (~ 7 second warning at 7 knots)

    - Implies Maximum Achievable Grazing Incidence Angle:

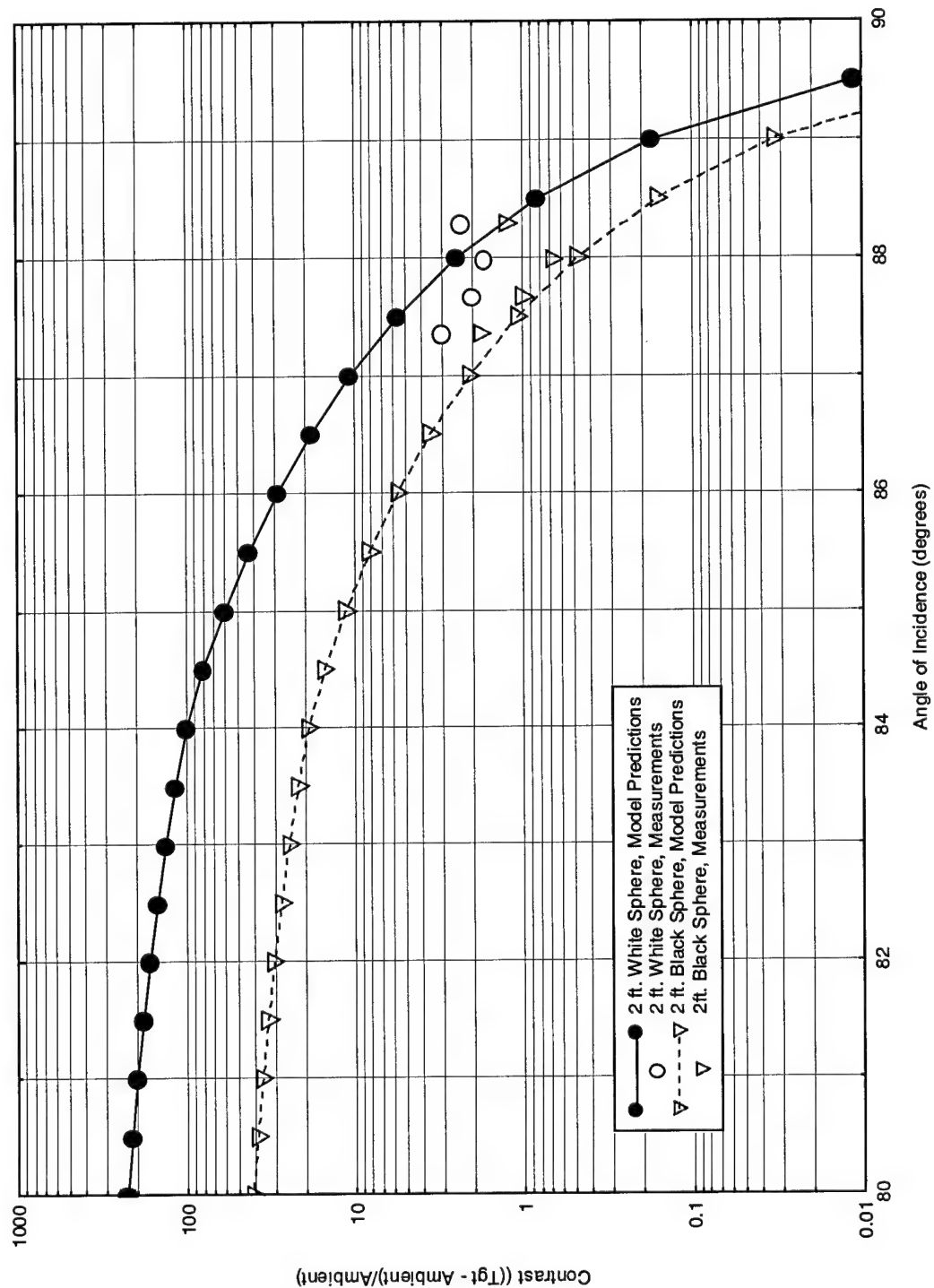   - ~1.7° High Speed Mode
        - ~2.5° Transition Mode

COMPARISON OF MODEL PREDICTIONS AND MEASUREMENTS OF TARGET RETURN SIGNALS

Legend:
- ● 2 ft. White Sphere, Model Predictions
- ○ 2 ft. White Sphere, Measurements
- ▽ 2 ft. Black Sphere, Model Predictions
- ▽ 2 ft. Black Sphere, Measurements

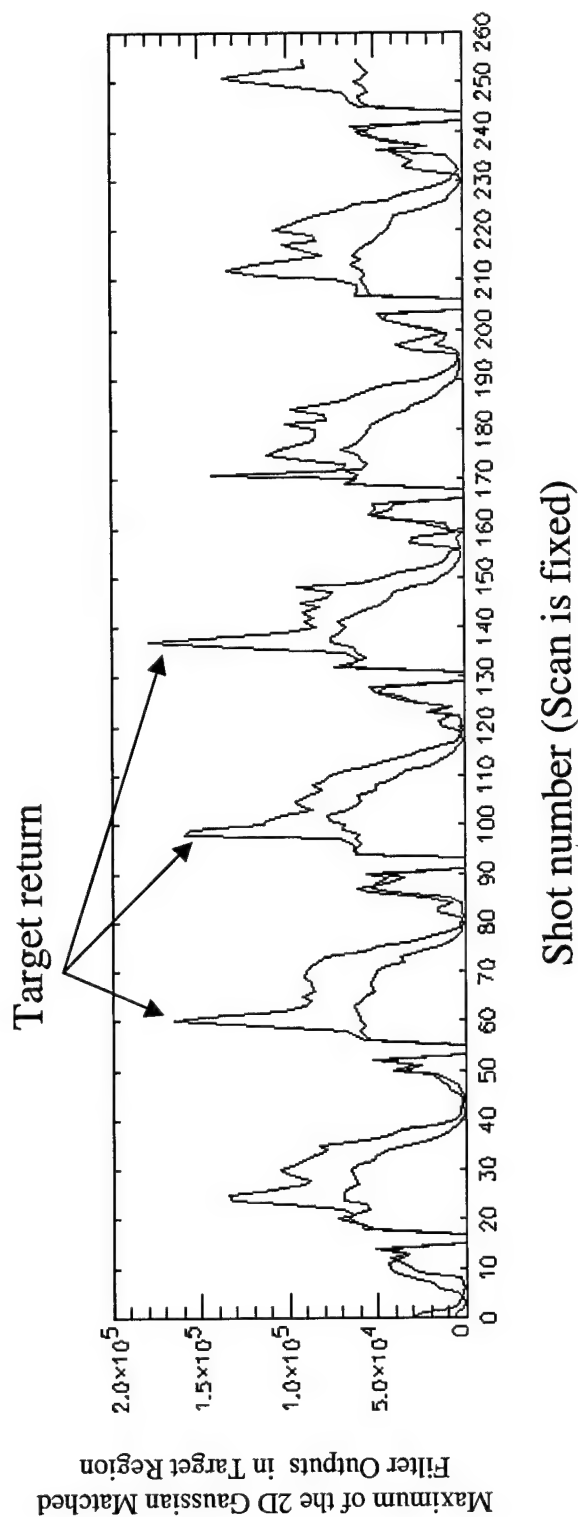X-axis: Angle of Incidence (degrees)
Y-axis: CCD Counts

COMPARISON OF MODEL PREDICTIONS AND MEASUREMENTS OF CONTRAST

EFFECTS OF WAVES ON LIDAR SIGNAL

- **Fluctuations in the Return Signal**

  - Periodic Bright Returns for Submerged Targets

  - Periodic Lower Level Returns for Water

  - Numerous Sporadic Very Bright Returns for Floating targets

- **Performed Statistical Analysis and Filtering on the Data**

  - Target vs. No Target

  - Waves vs. No Waves
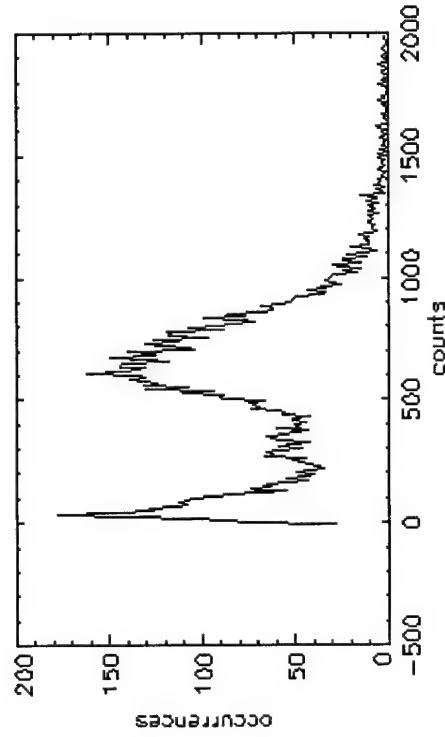
  - Floating vs. Submerged Targets

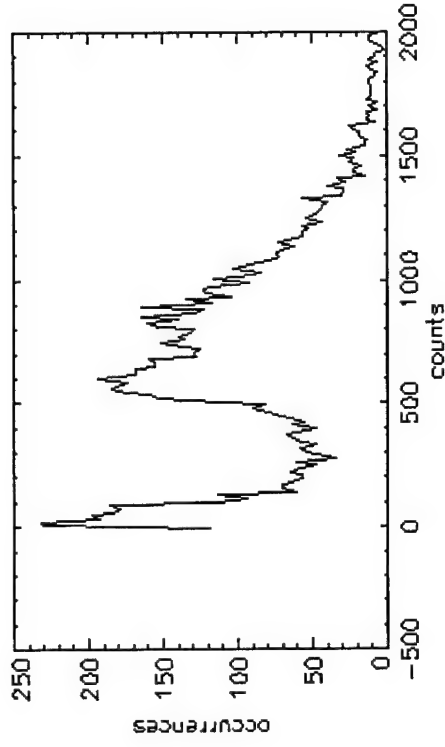# Periodic Returns for a Submerged Target due to Wave Action

Target return

Maximum of the 2D Gaussian Matched Filter Outputs in Target Region

Shot number (Scan is fixed)

- Wave Height (Trough to Crest): 17"
- Wavelength: 88'
- Grazing Angle: 2.3°
- Target: 2' diameter White Sphere
- Depth: Top of sphere at 6.75" below the surface
- Curves are for the peak outputs of the 2D Matched Filter for each shot:

  – Upper Curve: Target Returns

  – Lower Curve: No Target Region

Target Detection Histogram for Submerged Target
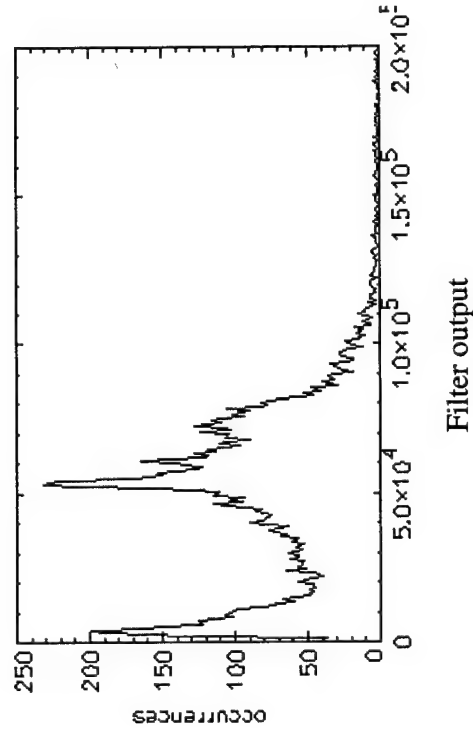## (Bias Subtracted Raw Data)

TARGET REGION

NO TARGET REGION

**TARGET DISTRIBUTION DIFFERS
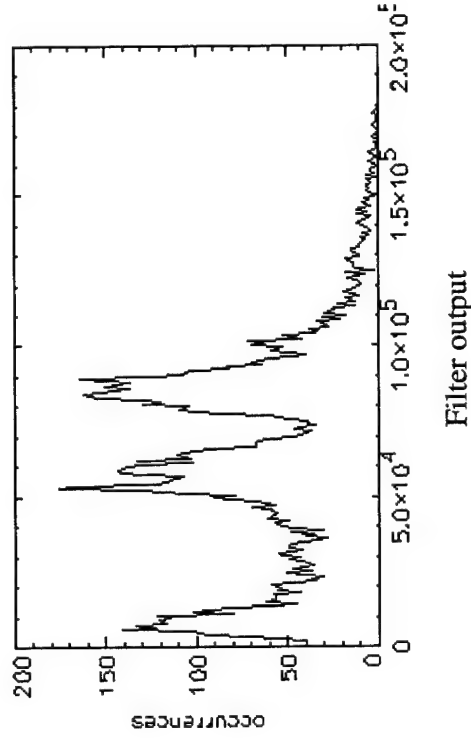FROM NO TARGET DISTRIBUTION**

Target Detection Histograms for Submerged Target
## (Output of the 2D Matched Filter)

NO TARGET REGION

TARGET REGION

- **FILTERING IMPROVES SEPARATION OF WATER AND TARGET RETURNS**

- **IMPLIES DETECTION POSSIBLE THROUGH FILTERING AND THRESHOLDING**

Comparison of Submerged Target Returns: Waves vs. No Waves
Matched Filter Output and Raw Data Histograms
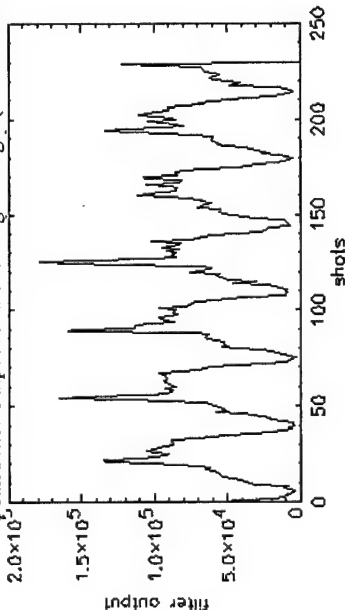### (High Power Aperture Product)

Histogram of Bias Subtracted Counts for a Submerged Target
(With and Without waves)
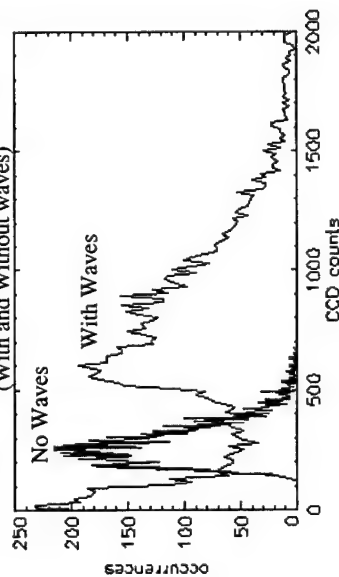
Histogram of Bias Subtracted Counts for No Target (With Waves)
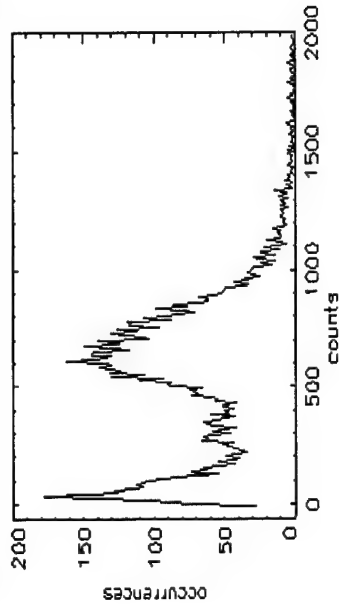
Peak Filter Output for a Submerged Target (With Waves)

Peak Filter Output for a Submerged Target (No Waves)
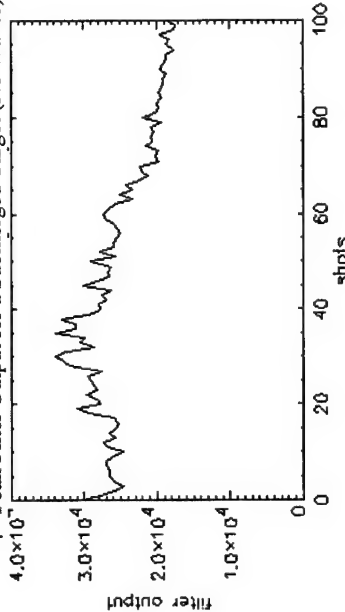
- **WAVES IMPROVE MEAN**
- **WAVES INCREASE FLUCTUATIONS**

Comparison of Submerged Target Return: Waves vs. No Waves

Matched Filter Output and Raw Data Histograms
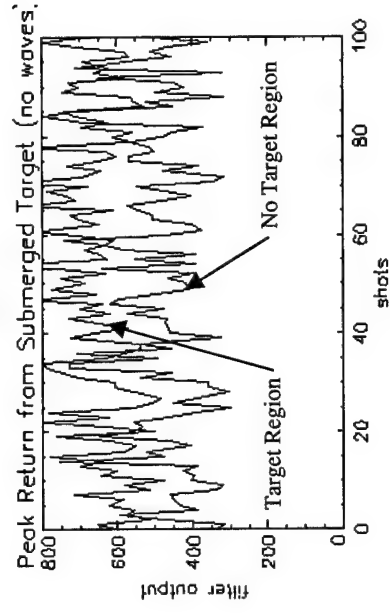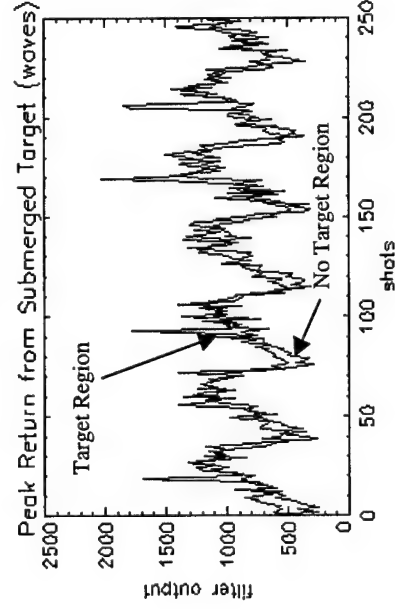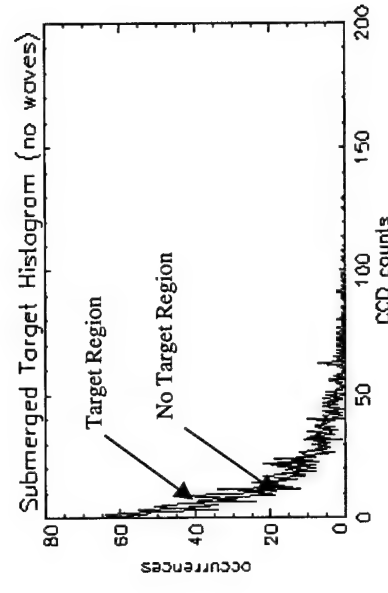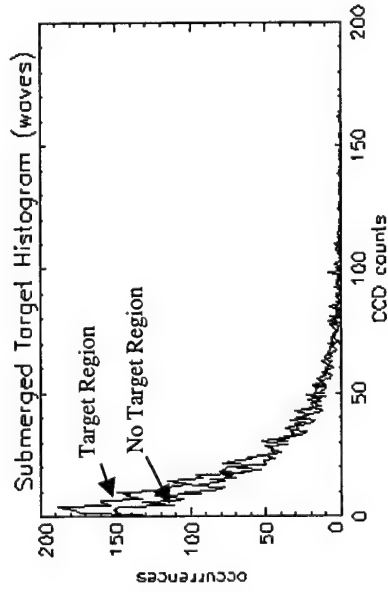
(Low Power-Aperture)

- **WATER AND TARGET RETURNS DIFFICULT TO SEPARATE AT LOW POWER-APERTURE**
- **IMPLIES TARGET IS DIFFICULT TO DETECT AT LOW POWER-APERTURE**

Comparison of Surface Target Return: Waves vs. No Waves
Matched Filter Output and Raw Data Histograms
Low Power-Aperture Product
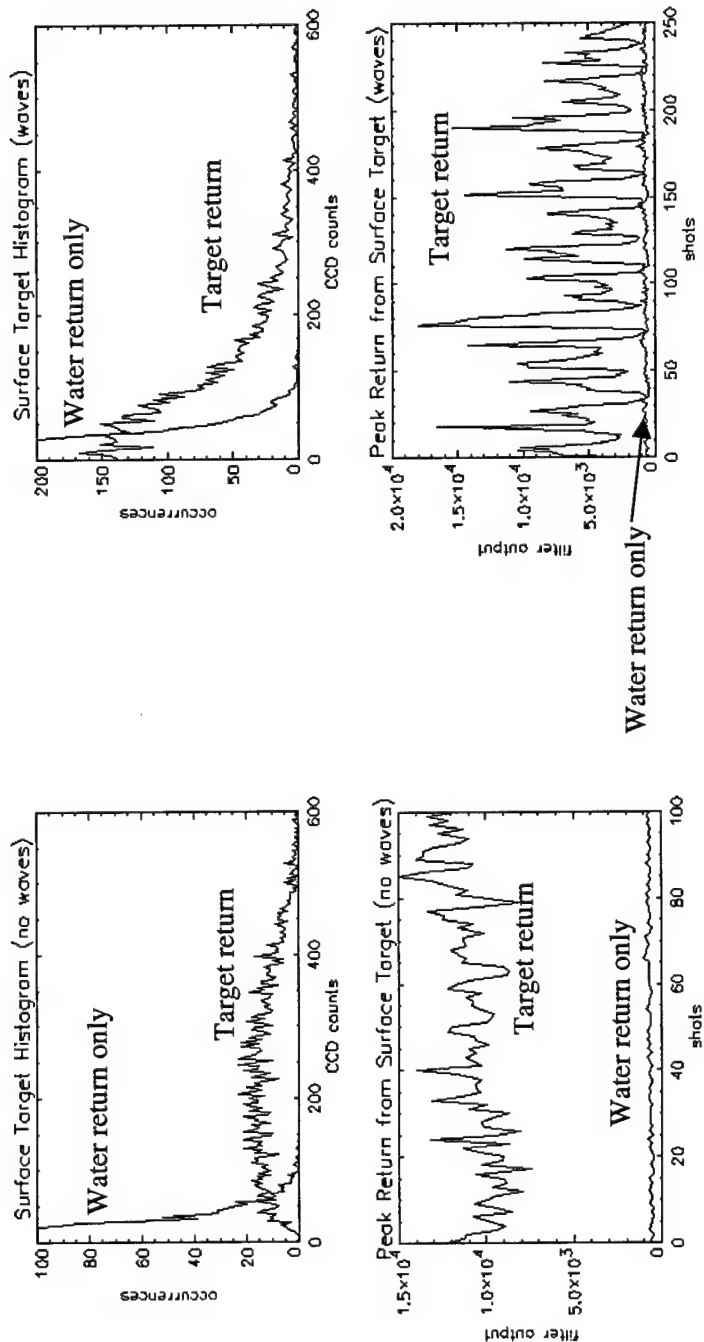
- **FLOATING TARGET RETURNS SEPARATE FROM WATER RETURNS IN ALL CASES**

- **WAVES DECREASE FLOATING TARGET MEAN AND INCREASE FLUCTUATIONS**

Detection of the Black, 1' Diameter Surface Target

Row Profile   Im135202 Image: 76

x = 31, y = 113, data coords: [189, 114]

Row Profile   Im142008 Image: 87

x = 44, y = 137, data coords: [197, 143]
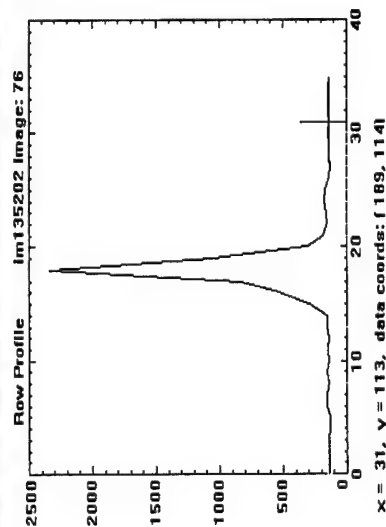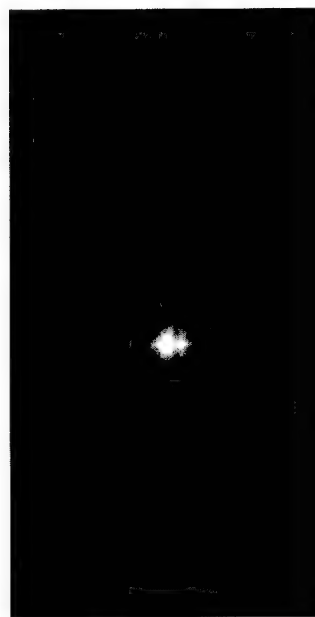
F/2, Gain 115, 46 mJ laser output

- 3.75 times lower power-aperture than used for the submerged targets (F/2, 172.5 mJ)
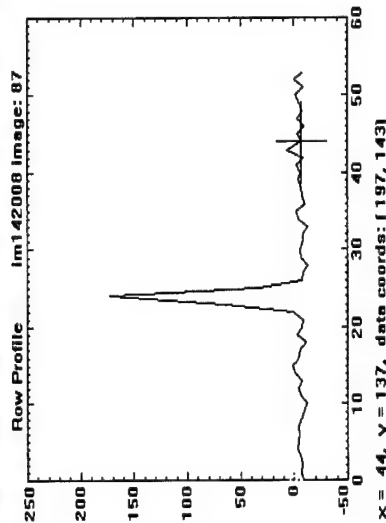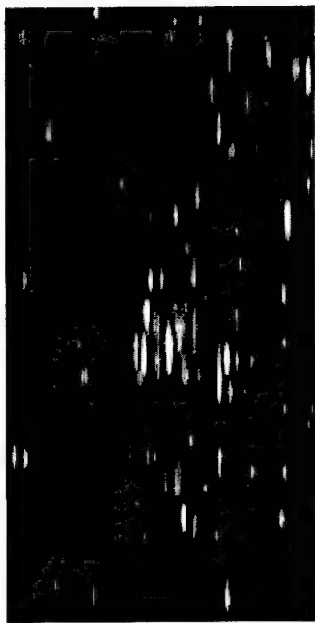
F/22, Gain 500, 21 mJ laser output

- 994 times lower power-aperture than used for the submerged targets

- FLOATING TARGETS DETECTABLE WITH A MUCH SMALLER, LOWER POWER SENSOR

BREAKERS TEST RESULTS

- **Floating Targets**
  - Easily Detected in All Cases
    - Detected at 994 times Lower Power-Aperture than Submerged Targets
  - Floating Targets are Much Brighter Than
    - Submerged Targets
    - Bottom
    - Water Surface
  - As Expected, Waves Degrade Floating Target Signal
    - Lowers Mean Signal
    - Increases Signal Fluctuations

- **Submerged Targets**
  - Detected at Grazing Angles greater than 1.7° at full power-aperture
  - Not Detected at Grazing Angles lower than 1.5° at full power-aperture
  - Not Detected at low power-aperture product at any tested grazing angle
  - Waves Improve Detectability if Observed over at least a Wave Period
    - Increases Mean Signal
    - Increases Signal Fluctuations

BREAKERS TEST RESULTS

- **Bottom**
  - Detected at All Incidence Angles at Full Power-Aperture
  - Not Detected at Low Power-Aperture

- **Water Surface**
  - Detected at All Incidence Angles at Full Power-Aperture
  - Not Detected at Low Power-Aperture

- **No Waves Data and the Modeling Agree**

CONCLUSIONS FOR PHASE I DATA ANALYSIS

- **Floating Targets on the Surface were Easily Detected**
  - Lower power-aperture product required for floating targets

- **Submerged Targets Require Large Power-Aperture for Detection**

- **Model and Test Results Agree**

- **Wave Effects:**
  - Benefit Submerged Target Detection
    - Improvement Not Enough for Reliable Detection at Low-Power Aperture
  - Degrade Floating Target Detection
    - Degradation Does Not Prevent Reliable Detection at Low-Power Aperture

PHASE I TRADE STUDIES

FOR

PHASE II TOP-LEVEL CONCEPT

MODEL PROJECTIONS FOR GRAZING LIDAR PERFORMANCE

- **Analytical Model Used to Assess the Following Effects**

  - High Speed Mode vs. Transition Mode

  - Sea State
    - Wave Heights
    - Wave Periods

  - Stand off distance

  - Observation Time

  - Pixel Format

  - Water Turbidity

  - Atmospheric Transmission - including Fog

- **Projections Computed for a Preliminary Conceptual Design for a Phase II Prototype**

  - Based on current state-of-the-art sensor technology and weight/size constraints

  - Concept Addresses Wave Effects for Sea State 3
    - Diverge beam along track to observe obstacle for at least one wave period

Preliminary Top-Level Conceptual Design
Illumination Geometry - Along Track, Calm Conditions, High Speed Mode
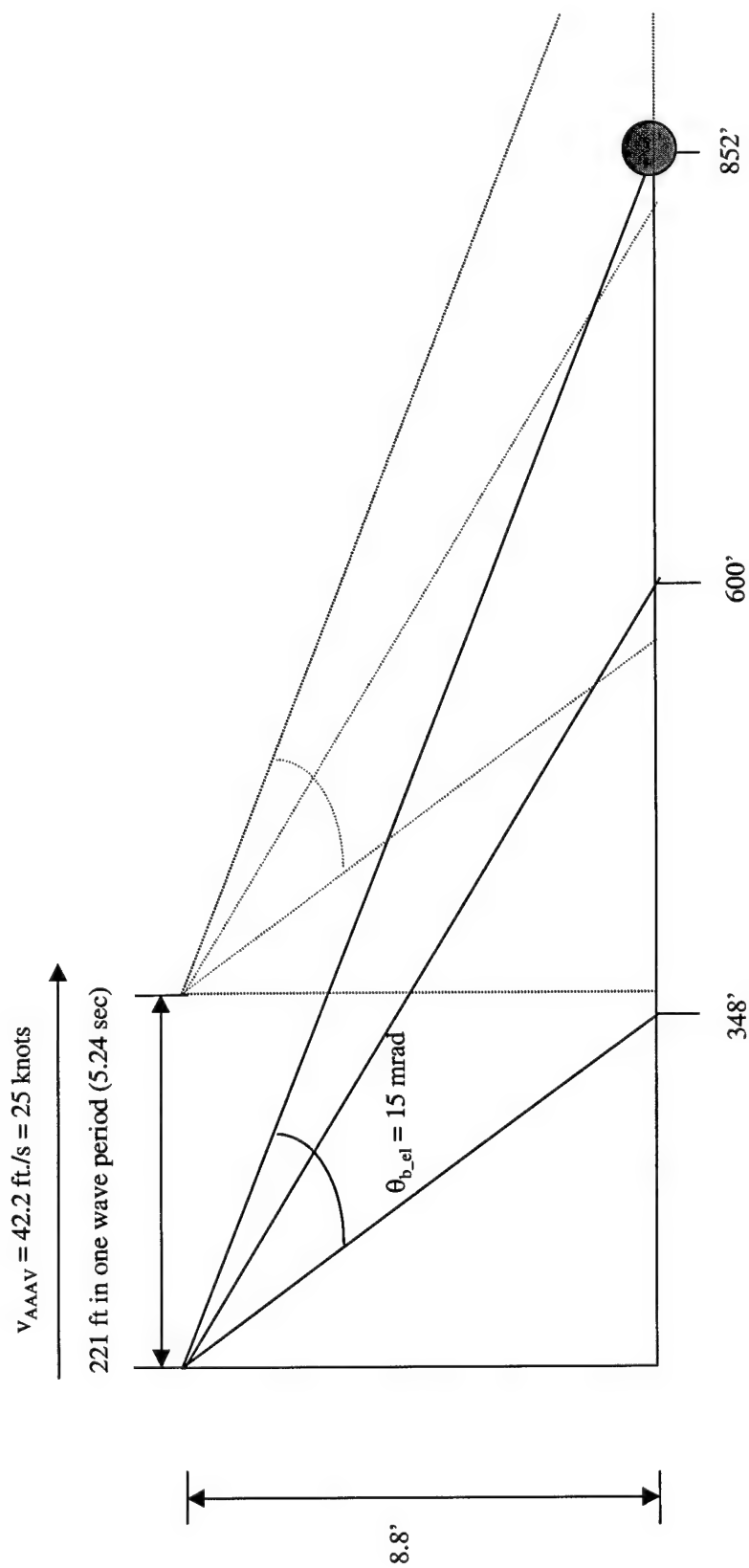
v_{AAAV} = 42.2 ft./s = 25 knots

221 ft in one wave period (5.24 sec)

θ_{b_el} = 15 mrad

852'

600'

348'

8.8'

Preliminary Top-Level Conceptual Design
Illumination Geometry - Along Track, Sea State 3, High Speed Mode
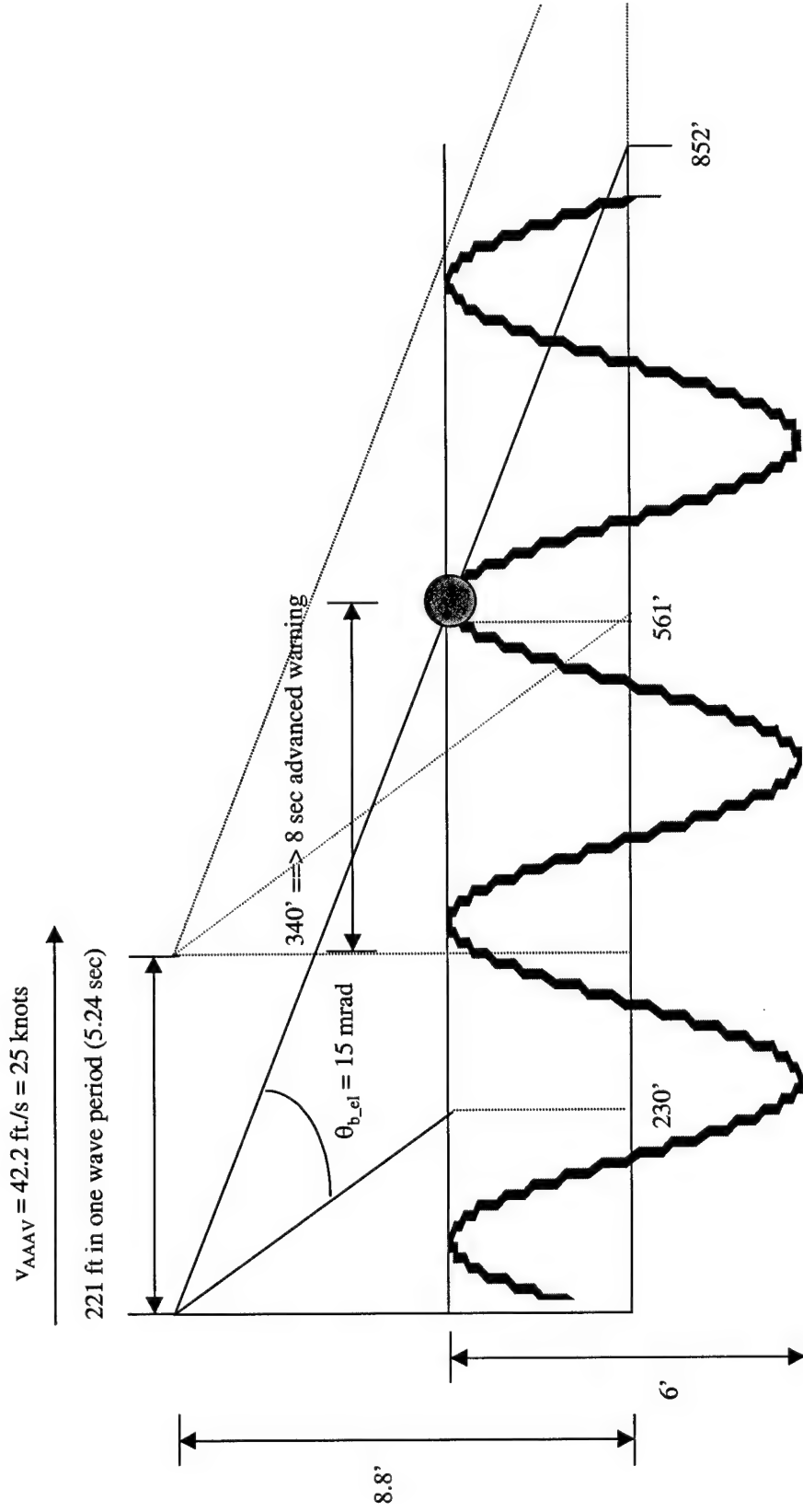
Preliminary Top-Level Conceptual Design
Illumination Geometry - Cross Track

Flat Surface Footprint
504' Along Track

44°

AAAV

852'

561'

348'

230'

6' Wave Height Footprint
331' Along Track
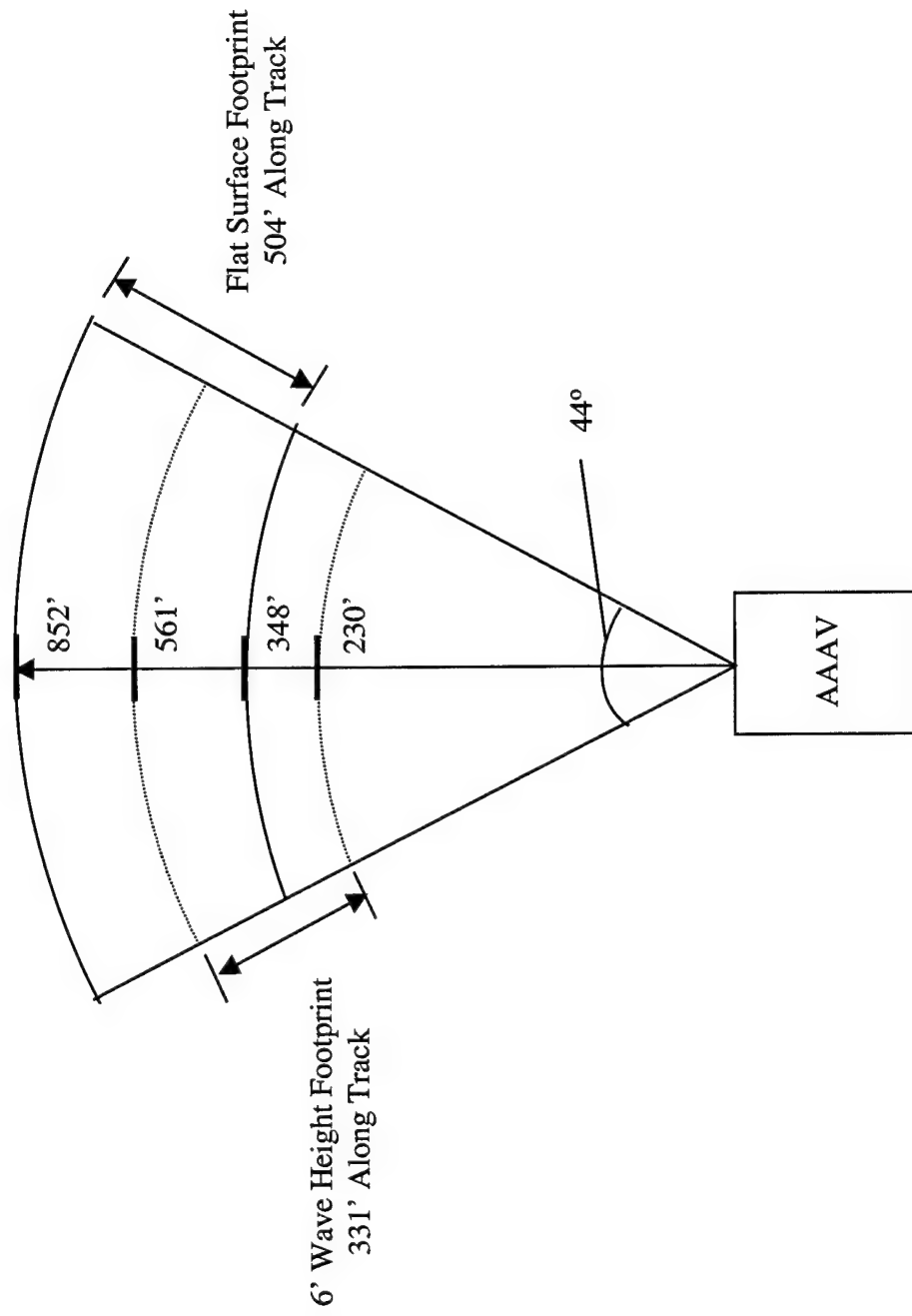
ELECTRO-OPTIC IDENTIFICATION (EOID) SYSTEM

- **System Developed for Underwater Mine Identification**

  - State-of-the-Art Compact Streak Tube Imaging Lidar

- **Provides Baseline for Phase II Prototype Design Trade Studies**
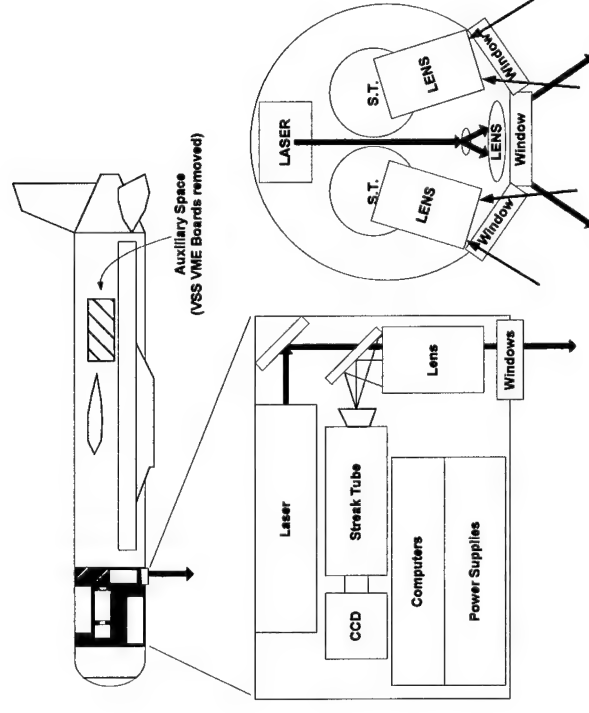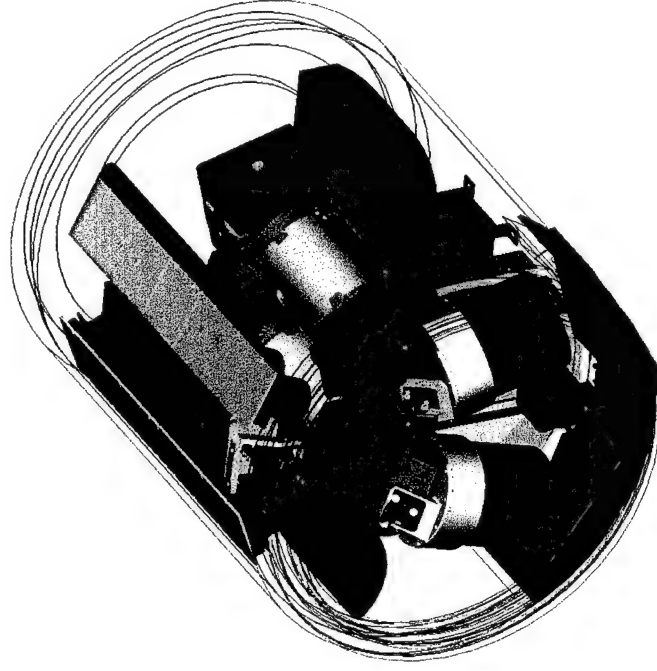
PHASE II PROTOTYPE TOP-LEVEL DESIGN PARAMETERS

- **Low Vignetting, Wide FOV Receiver Lens**
  - EOID Design
  - Receive Aperture: 36 mm (1.4"), Focal Length: 55.4 mm (2.18") (F/1.54)
  - 2.5:1 Fiber Optic Taper
  - Receiver Field-of-View (FOV): 15 mrad elevation x 44° azimuth

- **Streak Tube:**
  - EOID Spare
  - Photonis P930
  - 18 mm diameter photocathode
  - Sweep Delay: 450 ns (222' equivalent distance)
  - Sweep Duration: 1.3 µsec (639' equivalent distance)

- **SMD CCD array:**
  - EOID Spare
  - 256 x 1024 pixels switchable to 128 x 128 pixels frame
  - 30 Hz frame rate

PHASE II PROTOTYPE

TOP-LEVEL DESIGN PARAMETERS (CONT.)

- **Laser:**

  – EOID Spare (made by Cutting Edge Optronics)

  – 400 Hz PRF

  – 10 mJ/pulse

  – 4 W Average Power

  – 8 nsec Pulse Width, 532 nm Wavelength

- **Transmit Aperture:**

  – Diameter < 25.4 mm (1")

  – Cylindrical Lens & Lenticular Array

  – Transmit Beam Divergences: 15 mrad elevation x 44° azimuth

TRADE STUDY RESULTS

MODEL PREDICTIONS OF PROTOTYPE
PERFORMANCE FOR FLOATING TARGET DETECTION

(High Speed Mode)

Signal Counts vs. Range

for

1' Diameter, Dark Target and Several Visibilities

Clear(23 Km Visibility)
Hazy (5Km Visibility)
Moderate Radiative Fog (0.5 Km Visibility)
Heavy Advective Fog (0.15 Km Visibility)
Detection Threshold
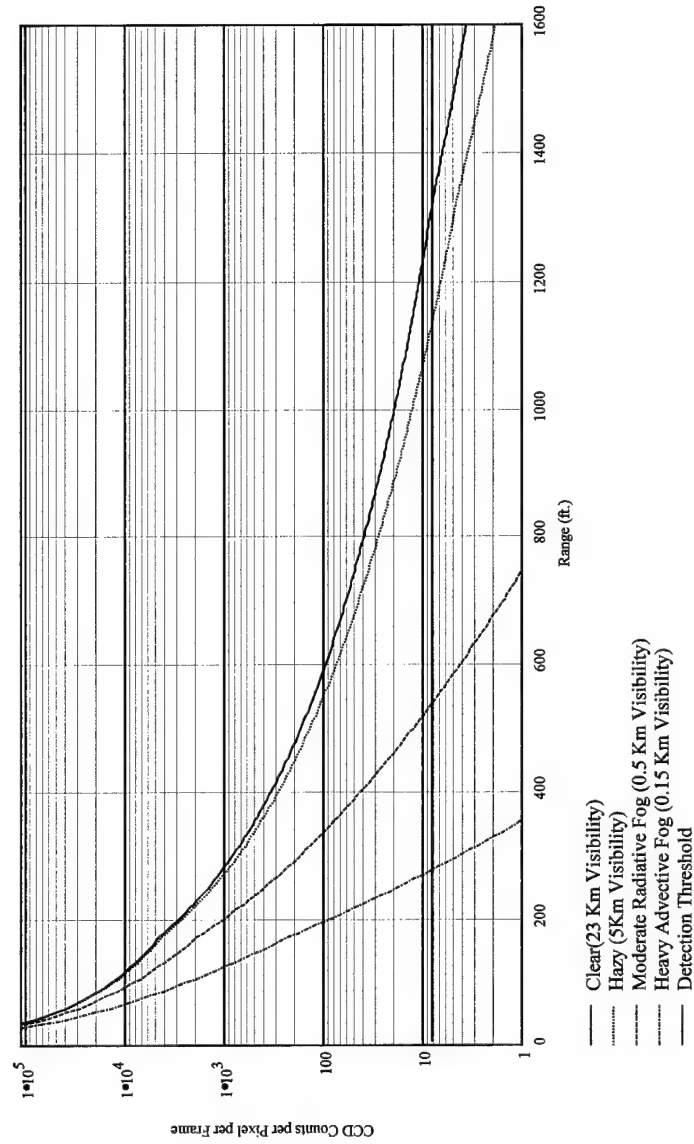
Floating Target Detectable In High Speed Mode To Significant Ranges
Even in Moderate Radiative Fog (500 m Visibility)

MODEL PREDICTIONS OF PROTOTYPE
PERFORMANCE FOR FLOATING TARGET DETECTION

(Transition Mode)

Signal Counts vs. Range
for
1' Diameter, Dark Target and Several Visibilities

Clear(23 Km Visibility)
Hazy (5Km Visibility)
Moderate Radiative Fog (0.5 Km Visibility)
Heavy Advective Fog (0.15 Km Visibility)
Detection Threshold

Floating Target Detectable In Transition Mode To Significant Ranges
Even in Moderate Radiative Fog (500 m Visibility)

MODEL PREDICTIONS OF PROTOTYPE PERFORMANCE FOR SUBMERGED TARGET DETECTION

(High Speed Mode, Beam Divergence Insures Wave Coverage, 256 range x 1024 az pixels)

Signal Counts vs. Stand-off Distance
for
1' Diameter Target at 10' Depth in Several Water Types

Legend:
- JWT II
- JWT III
- JWT 1
- JWT 3
- JWT 5
- JWT 7
- JWT 9
- Detection Threshold

Submerged Target NOT Detectable In High Speed Mode To Significant Ranges For Beam Diverged for Wave Coverage and Full Receiver Resolution

MODEL PREDICTIONS OF PROTOTYPE PERFORMANCE FOR SUBMERGED TARGET DETECTION

(High Speed Mode, Beam Divergence Insures Wave Coverage, 256 range x 1024 az pixels)

Signal Counts vs. Stand-off Distance

for

Bottom at 10' Depth in Several Water Types

Legend:
- JWT II
- JWT III
- JWT 1
- JWT 3
- JWT 5
- JWT 7
- JWT 9
- Detection Threshold

Y-axis: CCD Counts

X-axis: Stand-off Distance (ft.)

Bottom NOT Detectable In High Speed Mode To Significant Ranges
For Beam Diverged for Wave Coverage and Full Receiver Resolution

MODEL PREDICTIONS OF PROTOTYPE PERFORMANCE FOR SUBMERGED TARGET DETECTION

(High Speed Mode, Beam Divergence Fixed at 15 mrad, 256 range x 1024 az pixels)

Signal Counts vs. Stand-off Distance

for

1' Diameter Target at 10' Depth in Several Water Types

Submerged Target NOT Detectable In High Speed Mode To Significant Ranges For Beam Narrowed and Full Receiver Resolution

MODEL PREDICTIONS OF PROTOTYPE PERFORMANCE FOR SUBMERGED TARGET DETECTION

(High Speed Mode, Beam Divergence Fixed at 15 mrad, 256 range x 1024 az pixels)

Signal Counts vs. Stand-off Distance
for
Bottom Target at 10' Depth in Several Water Types

Bottom NOT Detectable In High Speed Mode To Significant Ranges For Beam Narrowed and Full Receiver Resolution

MODEL PREDICTIONS OF PROTOTYPE PERFORMANCE FOR SUBMERGED TARGET DETECTION

(Transition Mode, Beam Divergence Set for Wave Coverage, 128 range x 128 az pixels)

Signal Counts vs. Stand-off Distance
for
1' Target at 10' Depth in Several Water Types

Submerged Target NOT Detectable In Transition Mode To Significant Ranges
For Beam Diverged for Wave Coverage and Pixels Binned to Integrate Energy

MODEL PREDICTIONS OF PROTOTYPE PERFORMANCE FOR SUBMERGED TARGET DETECTION

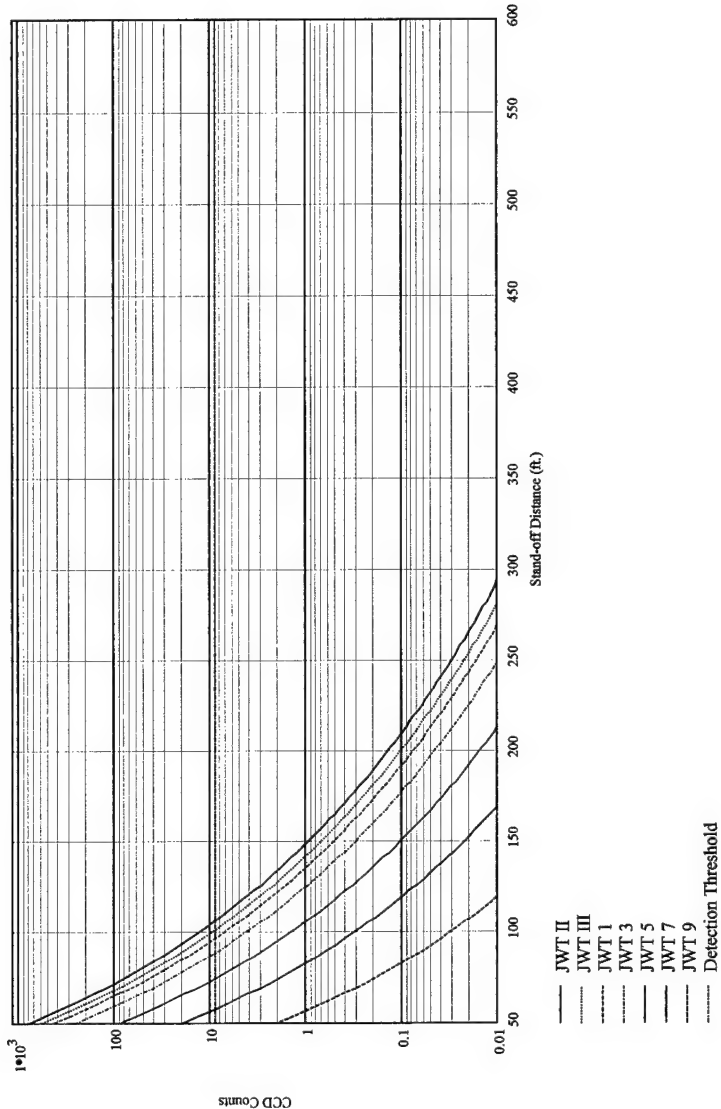## (Transition Mode, Beam Divergence Set for Wave Coverage, 128 range x 128 az pixels)

Signal Counts vs. Stand-off Distance

for

Bottom at 10' Depth in Several Water Types

Bottom Detectable In Transition Mode To Significant Ranges In Clear to Moderately Turbid Water For Beam Diverged for Wave Coverage and Pixels Binned to Integrate Energy

MODEL PREDICTIONS OF PROTOTYPE PERFORMANCE FOR SUBMERGED TARGET DETECTION
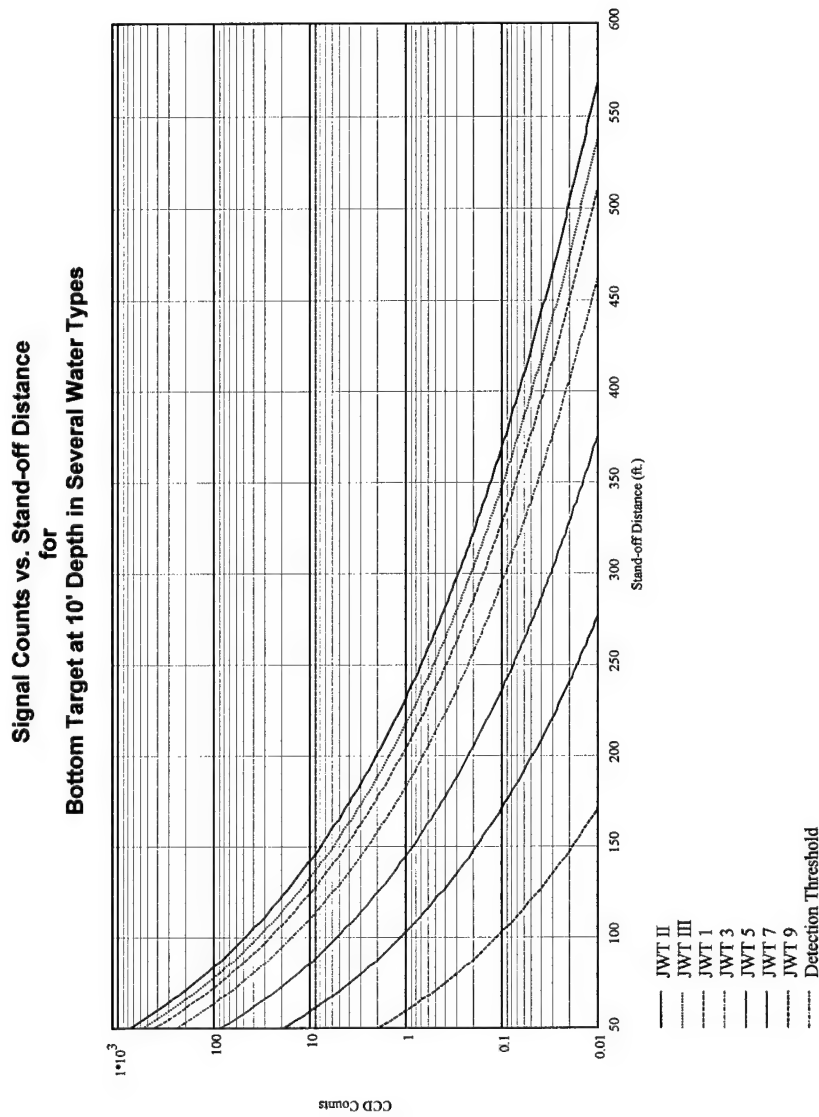
(Transition Mode, Beam Divergence Set at 15 mrad, and 128 range x 128 az pixels)

Signal Counts vs. Stand-off Distance
for
1' Diameter Target at 10' Depth in Several Water Types

Submerged Target Detectable In Transition Mode To Significant Ranges In Clear to Moderately Turbid Water For Beam Narrowed and Pixels Binned to Integrate Energy

MODEL PREDICTIONS OF PROTOTYPE PERFORMANCE FOR SUBMERGED TARGET DETECTION

(Transition Mode, Beam Divergence Set at 15 mrad, and 128 range x 128 az pixels)

Signal Counts vs. Stand-off Distance

for
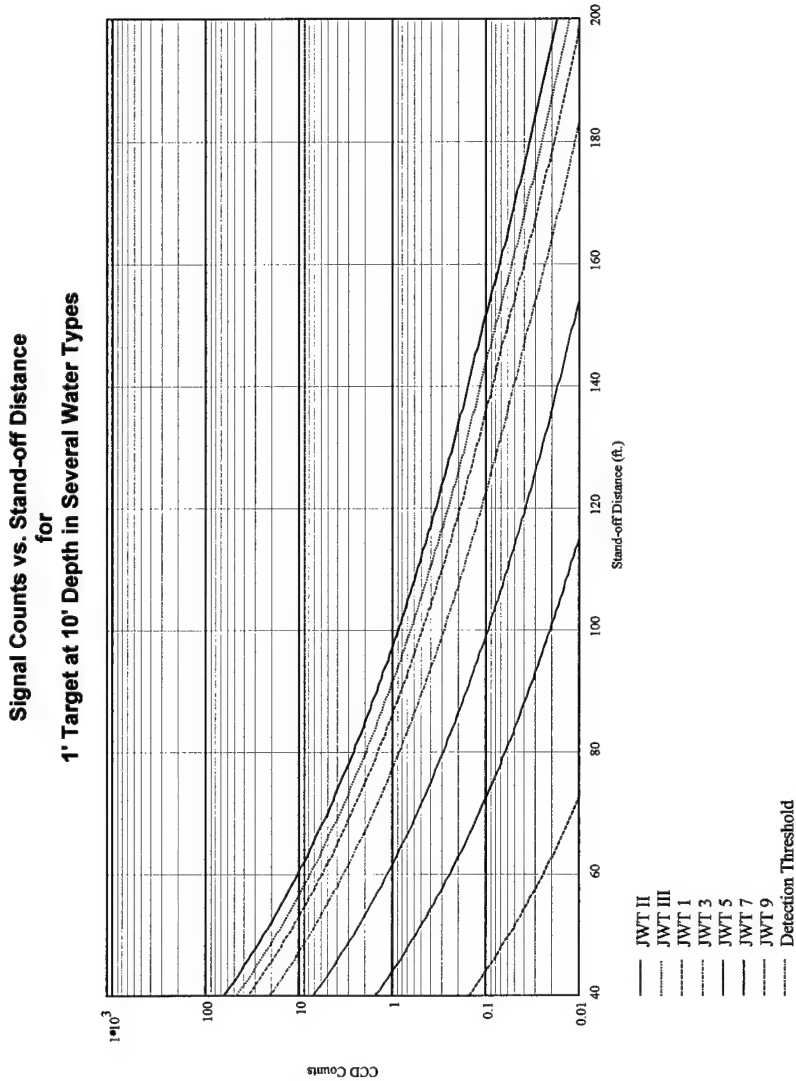
5' Diameter Target at 10' Depth in Several Water Types

Legend:
- JWT II
- JWT III
- JWT 1
- JWT 3
- JWT 5
- JWT 7
- JWT 9
- Detection Threshold

X-axis: Stand-off Distance (ft.)
Y-axis: CCD Counts
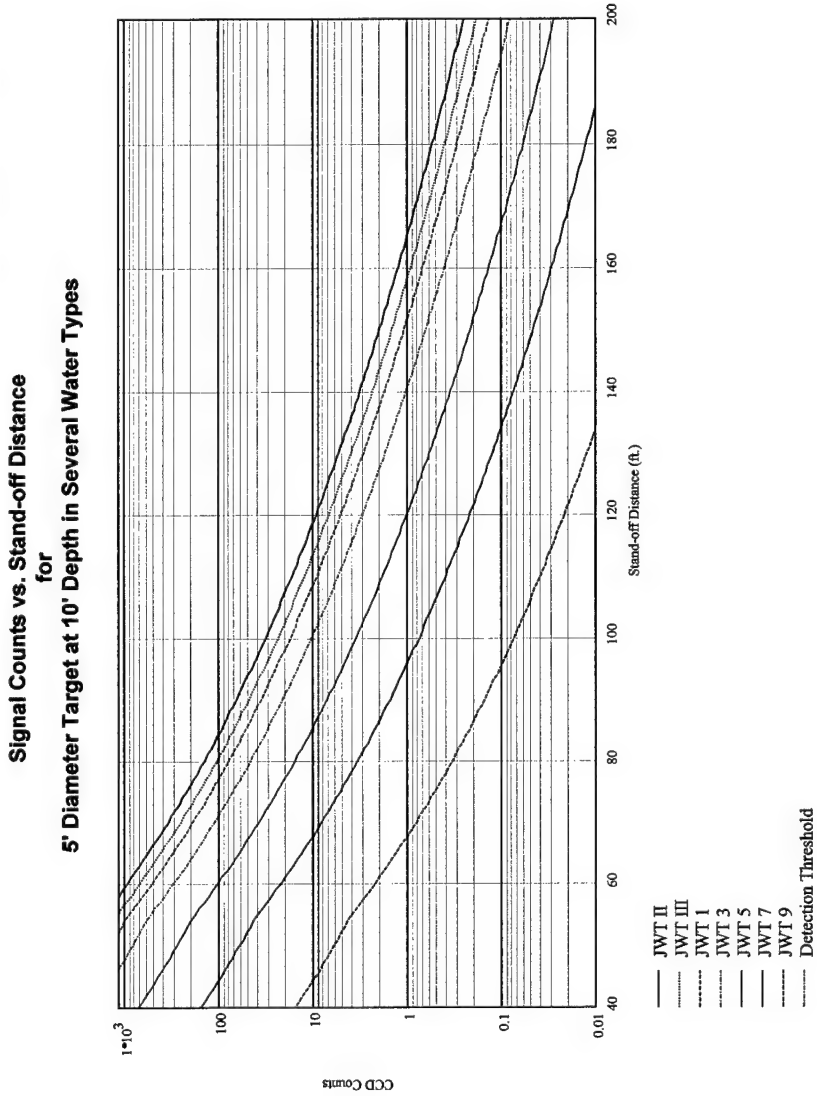
Larger Submerged Targets are More Detectable than Smaller Ones
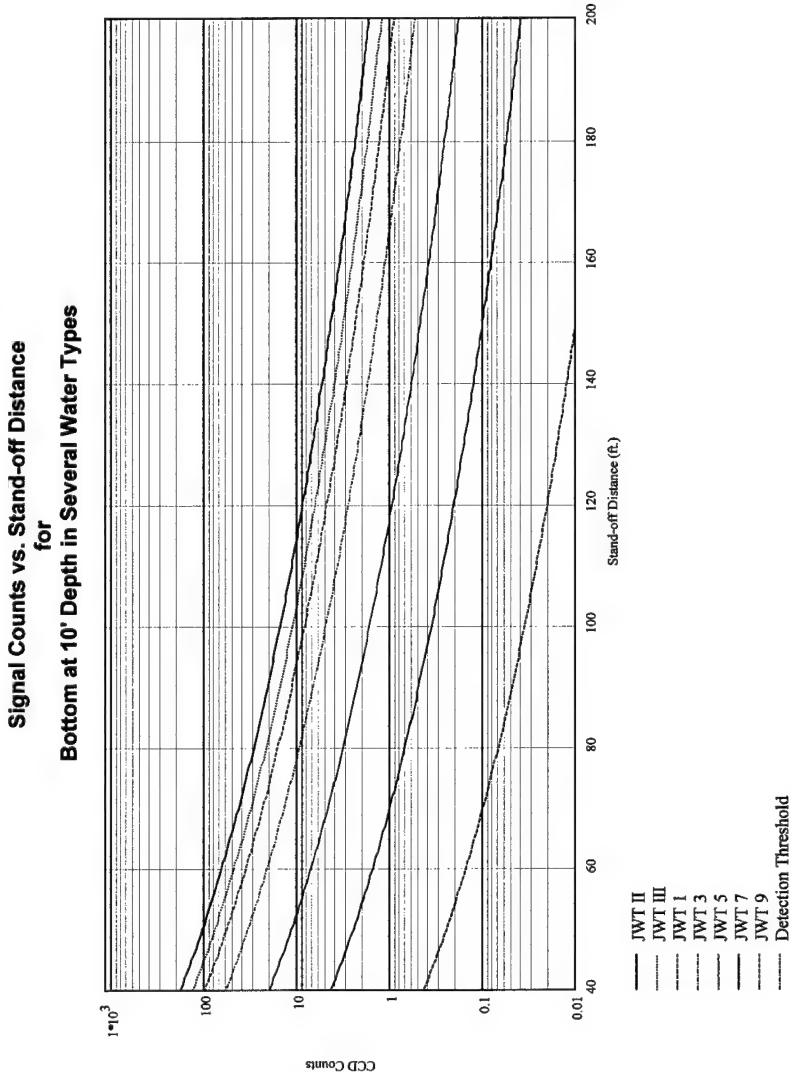### (Beam Narrowed and Pixels Binned to Integrate Energy)

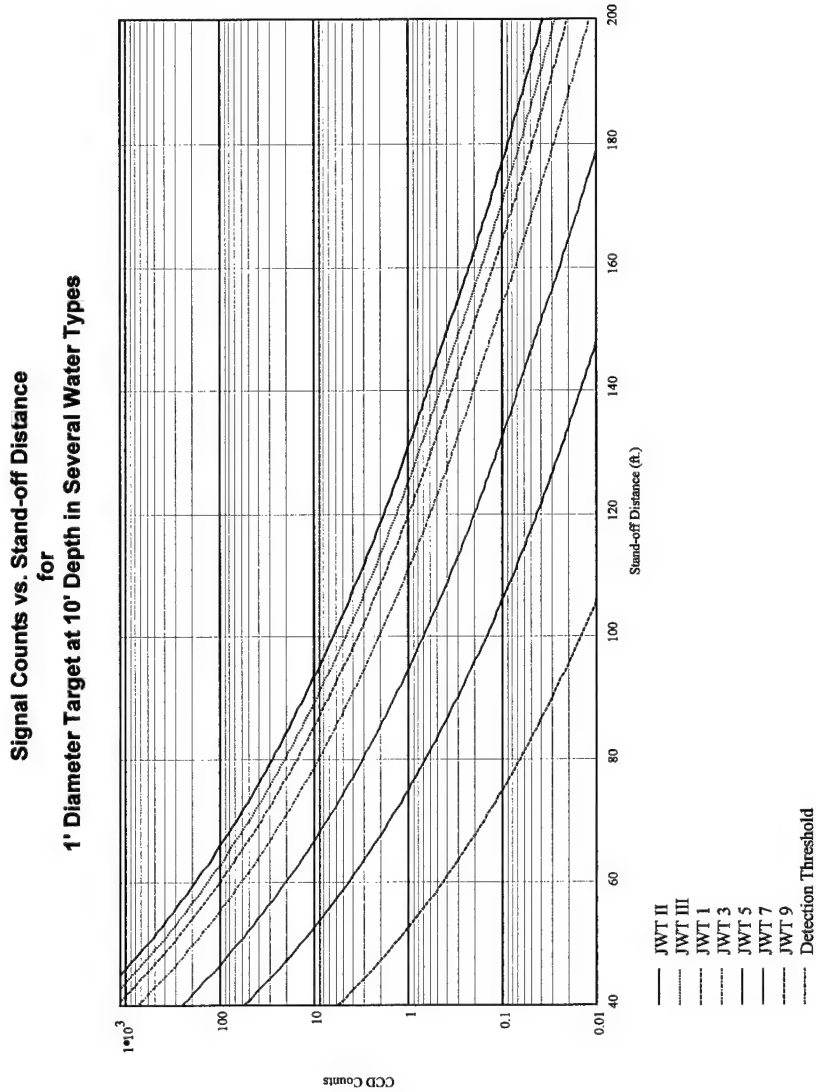# MODEL PREDICTIONS OF PROTOTYPE PERFORMANCE FOR SUBMERGED TARGET DETECTION

(Transition Mode, Beam Divergence Set at 15 mrad, and 128 range x 128 az pixels)

Signal Counts vs. Stand-off Distance
for
Bottom at 10' Depth in Several Water Types

Legend:
- JWT II
- JWT III
- JWT 1
- JWT 3
- JWT 5
- JWT 7
- JWT 9
- Detection Threshold

Axes: CCD Counts (vertical, $1 \cdot 10^3$, 100, 10, 1, 0.1, 0.01) vs. Stand-off Distance (ft.) (horizontal, 40, 60, 80, 100, 120, 140, 160, 180, 200)
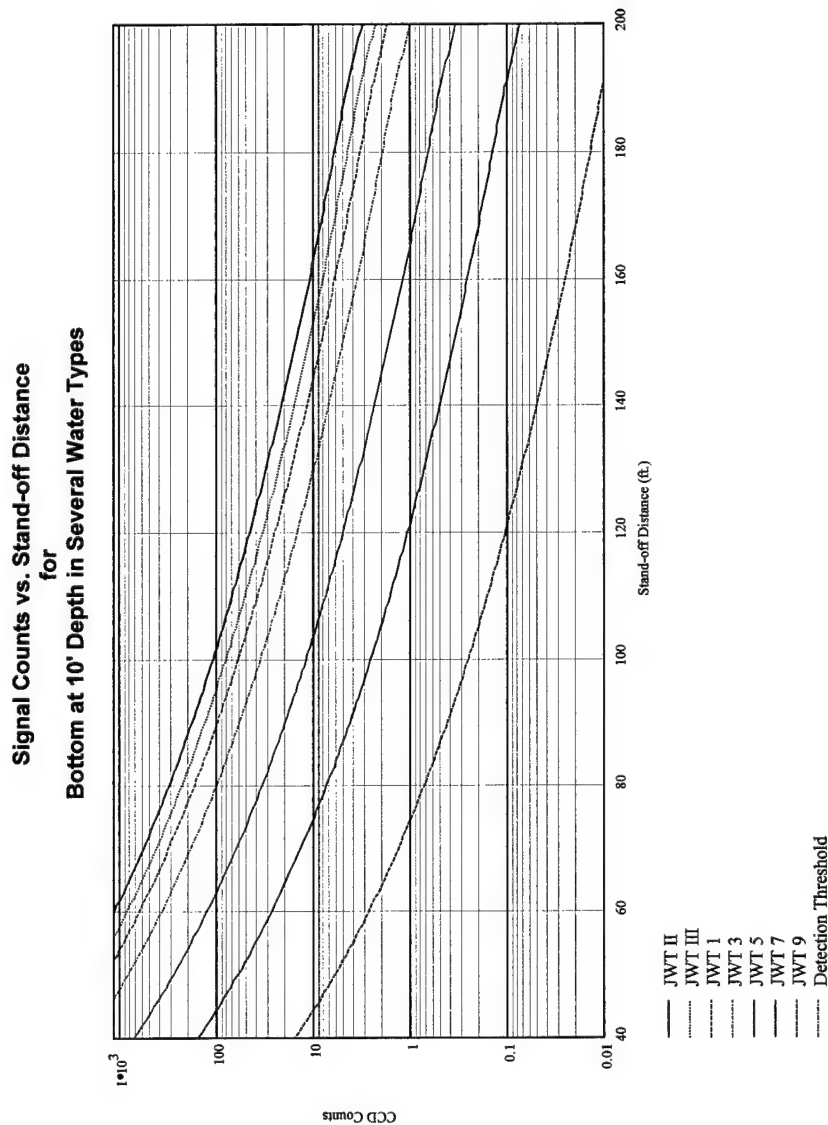
Extended Bottom is More Detectable than Small Targets
(Beam Narrowed and Pixels Binned to Integrate Energy)

EYE SAFETY FOR PROTOTYPE DESIGN

EYE SAFETY

- **Calculations Performed in Accordance with ANSI Z136.1-1993, American National Standard for Safe Use of Lasers**

- **Phase II Prototype with 15 mrad elevation x 44° azimuth beam divergences: NOHD = 85 feet**

- **Phase III System with 20 KHz PRF and 200 μJ per pulse, for 4 W average power, 15 mrad elevation x 44° azimuth beam divergences: NOHD = 20 feet**

- **Phase III System for Floating Targets Only could use 1.5μm wavelength to be Eye Safe at the Aperture**

  - 1.5 μm wavelength is several orders-of-magnitude more eye safe than shorter wavelengths

  - 1.5 μm wavelength is invisible and outside of the Image Intensifier Band and FLIR thermal bands

  - 1.5 μm wavelength penetrates haze and fog better than shorter wavelengths

  - 1.5 μm wavelength does not penetrate water

  - Arete persuing STIL at 1.5 μm through IR&D effort in collaboration with Hamamatsu which developed a 1.5 μm responsive streak tube

CONCLUSIONS FROM MODEL PROJECTIONS

- **Floating Target Detection Feasible for Compact Prototype in Both High Speed and Transition Modes**

    – Wave Effects addressed with large swath along track to provide long observation time

    – Design performs well under degraded atmospheric conditions

        • Down to 500 m visibility in Moderate Radiative Fog

    – Design is Eye Safe Beyond 85'

        • Phase III designs could be eye safe beyond 20' or even at the aperture (1.5μm)

- **Submerged Target/Bottom Detection Not Feasible with Sufficient Stand off Distance for Compact Prototype in High Speed Mode**

- **Submerged Target/Bottom Detection for Compact Prototype with Sufficient Stand off Distance in Transition Mode:**

    – May be Feasible for Large Targets and Extended Bottoms to 10' Depth in Moderately Turbid Water and Clear to Hazy Air

    – Reliability of Detection is at Issue because beam divergence is insufficient to allow observation over a full wave period

PHASE II OBJECTIVES AND PLANS

Phase II Design Philosophy

- **Make maximum use of existing hardware and software**
  - Maximizes funding for testing, analysis, and algorithm development
  - Lowers risk by using proven systems and methods
- **Make system mountable on AAAV for testing**
  - System will not be in final mechanical package

PHASE II OBJECTIVES AND WORK PLAN

- **Address Outstanding Issues**
  - Early Beach based tests with current Phase I Prototype
    - Collect Data on Real Ocean Waves and Turbid Coastal Water
    - Assess the effects of White Caps
    - Use data to develop and test algorithms

- **Perform System Engineering and Detailed Design**
  - Trade Studies to Optimize Design
  - Leverage EOID Design and Parts to meet budget and time constraints

- **Build Self-contained, Bolt-on Prototype**
  - Only interface to vehicle will be mechanical mounting and power
  - Provides ability to perform preliminary tests from other craft
  - Provides ease of installation/de-installation for tests
  - Prototype will consist of two parts
    - Mast mounted sensor head in stabilized mount
    - Operator Control and Display Station connected to sensor head via cables

PHASE II OBJECTIVES AND WORK PLAN (cont.)

- **Develop and Implement Real-Time Detection and Clutter Rejection Algorithms for the Prototype**

  - Leverage Real-time Detection/Classification Algorithms from EOID

  - Leverage Real-time DSP architectures from EOID

  - Test against real ocean data

- **Test Stabilization Platform and Servo Control Algorithms**

  - Leverage Servo Control Algorithms from AROSS Project

  - Ground Tests with Integrated Sensor Head at local Race Track Prior to full system testing on the ocean

- **Full System Testing**

  - Beach Based Static Tests to Debug Hardware and Software

  - Ocean Tests from Commercial Craft

  - Bolt On AAAV for Prototype Full System Tests

PHASE II OBJECTIVES AND WORK PLAN (cont.)
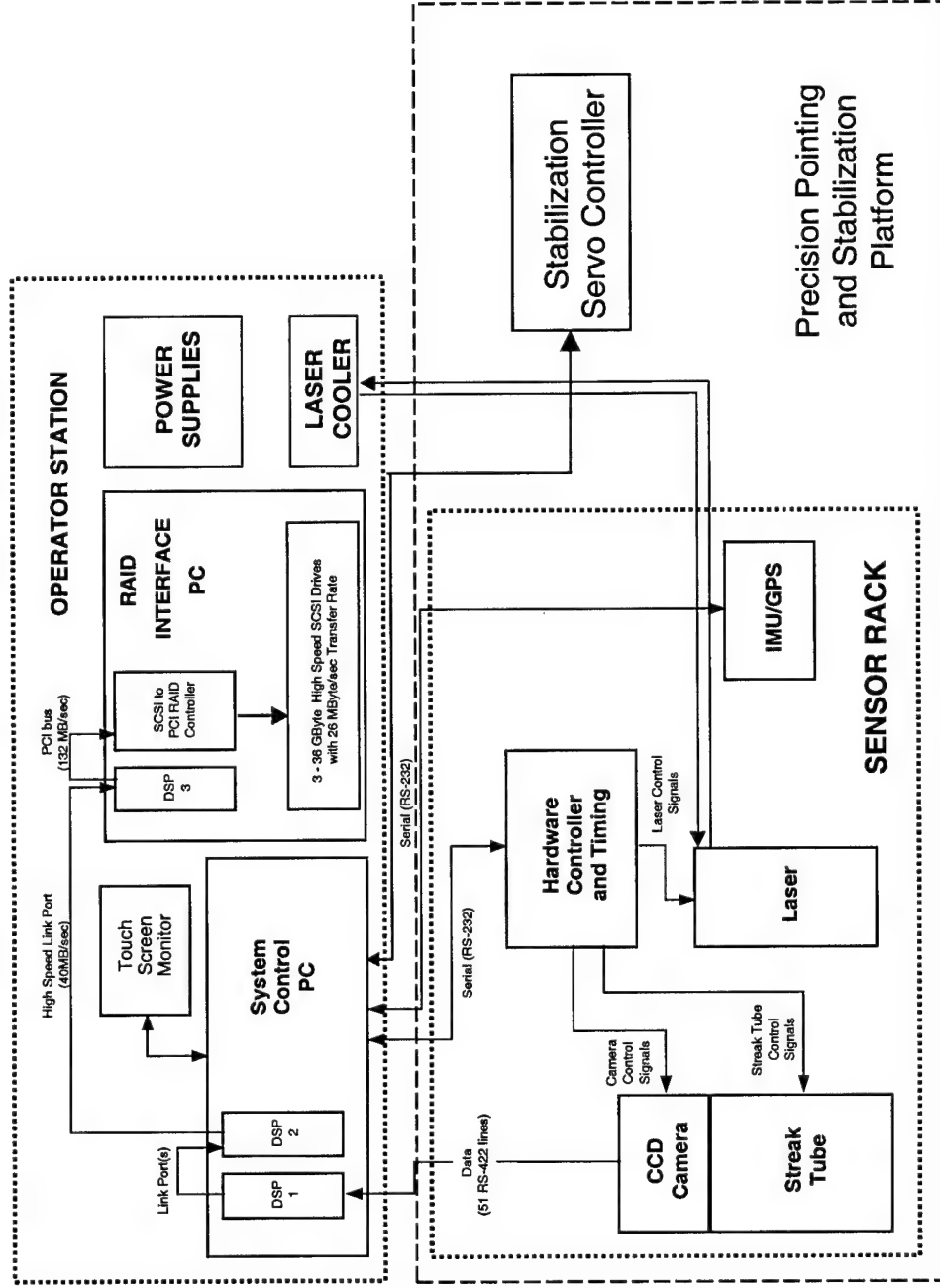
- **Phase III Prototype Top-Level Conceptual Design**

  – **Leverage New Compact High Rep Rate, High Average Power Diode-Pumped Lasers**

    • Smaller, Lighter, More Efficient (less heat and less power consumed), Phase Change-cooled systems

    • Eye Safe at a Shorter Range than Lower Rep Rate Lasers with same average power

  – **Mechanical Packaging to make compact and robust**

    • EB-CCD Streak Tube - Eliminates Phosphor and Fiber Optic Window

    • Compact Streak Tube - New electron optics and packaging designs for smaller tubes

    • Reduce size and power consumption of Processing hardware - single chip, custom FPGA DSPs

    • Compact Stabilization Mount - lower weight and size of components will lower weight and size of mount

  – **Identify Integration Issues with the AAAV Systems**

PHASE II PROTOTYPE FUNCTIONAL DIAGRAM

Fan Beam

Diverging Optics

15 mrad x 44o Beam Divergence

Pulse Energy

F/1.54, D = 36 mm, f = 55.4 mm, FOV = 44°

Imaging Optics

Power Cooling

Laser

4 W average, 10 mJ, 400 Hz

Trigger

Delay Generator

Trigger

HV Sweep

Streak tube

256 range x 1024 azimuth / 128 range x 128 azimuth pixels

Data

Control

Control

Trigger Exposure

CCD

Image Data

Image Data - RS 422

Auxiliary Data - RS 232

Control - RS 232

Hardware Timing and Control

30 Hz Frame Rate

Image Processing

Operator Station

Data Storage

PHASE II PROTOTYPE BLOCK DIAGRAM

EOID Dual Receiver Prototype

# PHASE II BASELINE CONCEPTUAL DESIGN BASED ON EOID SYSTEM

- **Reduce Non-Recurring Engineering Costs, Time, and Risk by Leveraging Proven Designs and Hardware**

- **State-of-the-Art Compact Dual Receiver Streak Tube Imaging Lidar developed by Arete for ONR**

  - 400 Hz, 10 mJ/pulse green laser and 2 receivers

    - 36 mm Diameter, 55.4 mm focal length, 44° FOV per Receiver

    - Spare receiver assembly without optics available for this project.

    - Spare transmitter laser available for this project

  - Real-time Aided Target Detection and Identification

    - Leverage EOID developed real-time target detection algorithms

  - Completed by end of 2000

  - Control hardware and software based on extensions of proven EOID design

Detection Algorithm

- Based on Phase I Matched Filter Results
  - Can use EOID Filter and Threshold Algorithm
- Detection only needs 2 pixels across targets
  - Bin data to fewer, larger pixels
  - Successive binning tests for object match at different scales
  - Reduces data to be processed by up to 100x
  - Real-time implementation of matched filtering
- Operates on both range and contrast images
  - Shadow detection possible for low reflectance targets
- Description
  - Find peak values in binned frame
  - Find all pixels above threshold around the peak
  - Process successive frames of detected target data to reject noise and clutter by motion and correlation frame-to-frame
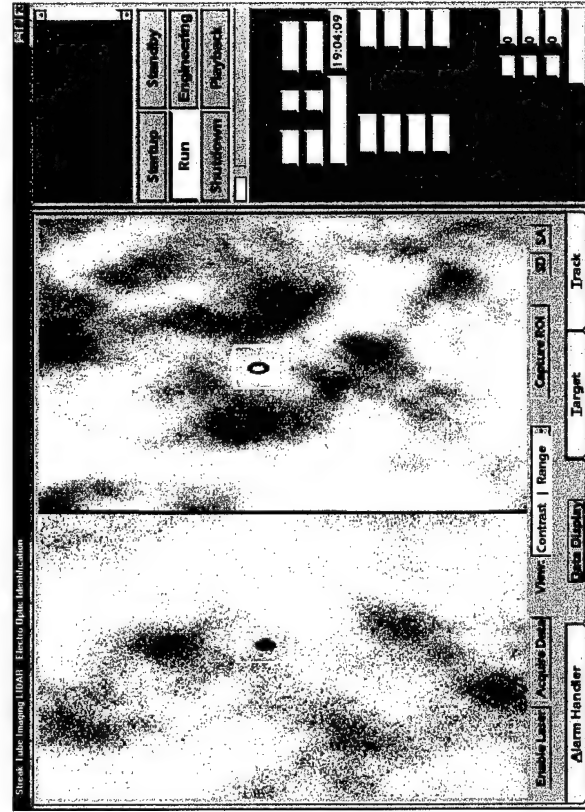 - Repeat process as new data is acquired

EOID Automatic Detection Algorithm
For Real Ocean Data
(Threshold Set at 1.25 σ)
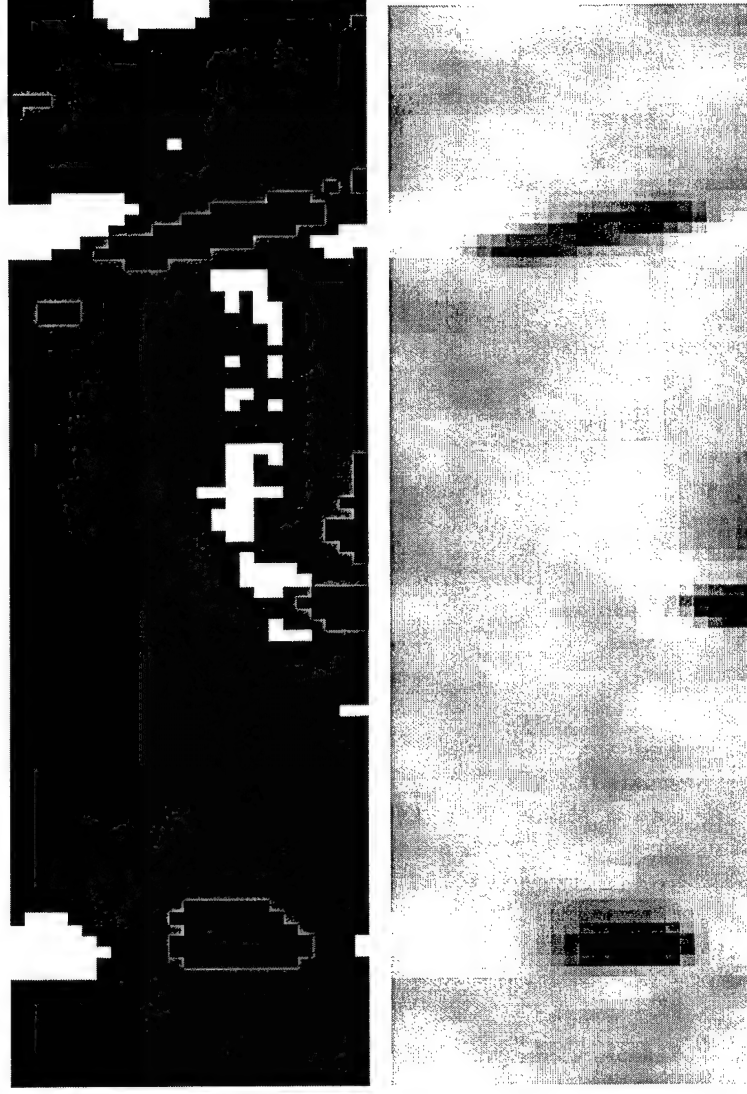
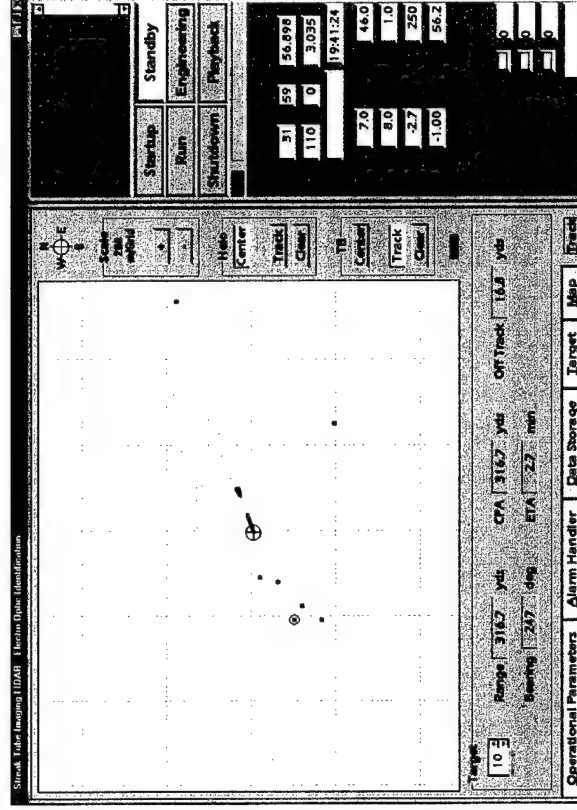## Both Bright and Dark Objects Detected by Algorithm

OPERATOR INTERFACE AND DISPLAY


EOID Operator Interface and Display 2:
"Track" Display Showing Current and Past
Positions of the Vehicle with Respect to Targets

EOID Operator Interface and Display 1:
Real-time Waterfall Display of Detected Targets

PHASE II PROTOTYPE POINTING STABILIZATION

- Pointing Stabilization Prevents Holes In Coverage

- Stabilization against Ship Pitch & Roll Required
  - AAAV Pitch Excursion: Up to +/- 12° at 12° per second
  - AAAV Roll Excursion: Up to +/- 10° at 10° per second
  - +/- 300 μrad Accuracy provides sub-pixel stabilization

- COTS Positioner from Xybion
  - +/- 95 μrad accuracy with +/- 25 μrad repeatability
  - 100 μrad line-of-site stabilization
  - 0.01° to 90° per second slew rate
  - PC control of the positioner available to integrate with Operator Station

- Sensor Rack (laser, hardware controller, streak tube, CCD camera, and IMU/GPS) mounts on the Positioner

XYBION POSITIONER

10.5"
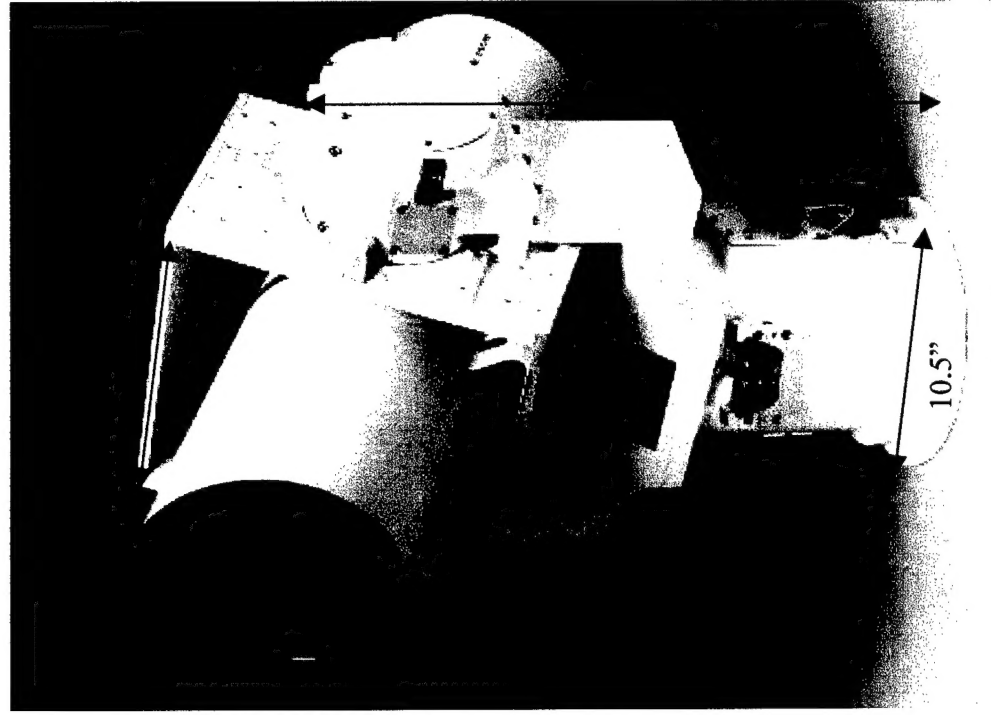
Phase II SCHEDULE

Quarters After Contract Award	1	2	3	4	5	6	7	8	9	10
TASKS									OPTION	
1. Phase I Prototype Ocean Testing	↑									
2. System Engineering & Trade Studies		↑								
3. Transceiver Design & Fabrication				↑						
4. System Control and Processing		↑			↑					
5. Mechanical Packaging and Stabilized Mount						↑				
6. Integration and Lab Tests							↑			
7. Field Tests and Demos		↑						1 ↑	2 ↑	3 ↑
8. Data Analysis and Performance Assessment								↑		
9. Phase III Conceptual Design								↑		
10. Final Report										↑

1. Track & BeachTests   2. Commercial Vehicle Ocean Tests   3. Tests on AAAV

PHASE I OPTION PLAN
"Initiating the System Design"

- **Assess Phase II Objectives and Requirements**

- **Perform Trade Studies based on Phase I Results**

  – Extend Phase I Trade Studies

  – Get Feedback from Sponsor on Vehicle Integration and Operation Issues

- **Initiate Phase II Preliminary Design**

  – Transceiver Optics

  – System Control Hardware

  – System Control Software

  – Data Transfer and Processing Architecture

  – Data Storage

  – Data Display

  – Interfaces

  – Mechanical Packaging and Mounting

  – Stabilized Mount Interface and Control

  – AAAV Interface & Mounting

Summary

- Detected Surface and Submerged Targets in Phase I

- Identified system performance envelope
  - Fog effects, turbidity, incidence angle, waves

- Developed Phase II Top-level Design Concept and Plan
  - Takes maximum advantage of existing hardware/software
  - Easy to install and de-install from AAAV
  - Will collect real sea data early, and will use the data for algorithm development (object detection/clutter rejection)

- Excellent Performance for Floating Targets in Both Modes
  - Detects floating targets at long range very well
  - System may be able to migrate to eyesafe wavelength if this is the preferred operating mode

- Submerged Target Detection
  - Possibly in Transition Mode, but reliability of detection is an issue
  - Not likely in High Speed Mode